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Making Complex Network Analysis in System Dynamics

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Abstract

As urban models in system dynamics are extremely complex if an area is subdivided in many dynamic and interacting areas, managing complexity of the urban network interactions is essential. A recently developed interregional model of The Netherlands illustrates the implementation of the spatial dimension in urban dynamics. The model describes 40 self-organizing urban areas and distribution of migrants, firms and commuting between 40 regions simultaneously. Developments in regional labor markets, housing markets and land-use can be explained by internal as well as by external regional conditions.

The applied approach gives many opportunities to make large disaggregated models in system dynamics. Spatial or sectional interactions (network models) can be modeled while model structures remain manageable. In general, as vector-based and matrix-based calculations can be implemented in system dynamics easily, many (existing) static models can be applied dynamically. Hence, the usefulness of system dynamics in modeling complex systems broadly is enlarged.

Key words: Network Analysis, Urban Dynamics, Spatial Interaction, Managing Complexity

History of urban dynamics

Jay W. Forrester's publication *Urban Dynamics* in 1969 introduced a new perspective on analyzing urban problems, forming a bridge between engineering and the social sciences. Urban dynamics research programs started in order to integrate the urban dynamics perspective into the decision-making processes of urban areas (Alfeld and Graham, 1976). Several applications of urban dynamics are made since, giving more understanding of urban behavior and how the urban system can be managed.

Although system dynamics and its application to the dynamic modeling of social systems might be one of the most insightful system dynamics applications ever developed, urban dynamics generated intense controversy (Alfeld, 1995) and practically died out in the seventies. Only a few remarkable academic publications are left and the hope that urban dynamics will revive one day.

This paper describes fundamental criticism of urban dynamics and how these critics can be reduced. A case study of The Netherlands describes regional socioeconomic changes of 40 regions, all interacting with each other. The approach used may not only inspire and therefore contribute to the field of urban dynamics, but gives –more in general- many opportunities to make large disaggregated models of different fields of study in system dynamics while model structures remain manageable. The usefulness of system dynamics in modeling complex systems is thereby enlarged.

Understanding traditional urban dynamics

As many systems the urban system is complex, which behavior is dominated by many nonlinear feedback processes. Traditional urban dynamics models show an urban area as a complex multi-loop structure of industry, housing and people. Two important driving forces that control urban behavior and give opportunities for an effective decision-making process are (1) resource constraints, and (2) relative attractiveness (Alfeld, 1995). These forces define the principal interactions of the urban area. Figure 1 summarizes overall interactions between population, business, houses and business structures, which are all regulated by an area's resources.

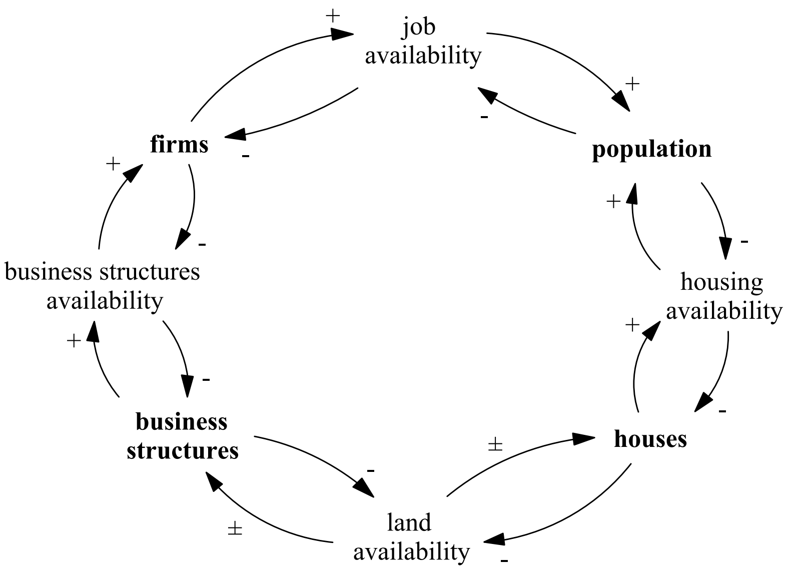

Figure 1 Traditional interactions between population, business, houses and business structures in urban dynamics

Figure 1 illustrates that if the population increases, the availability of housing will decline, for people will have to live somewhere in the area. As the population increases, the availability of jobs also declines because people will have to work in order to obtain money to buy food, clothing and shelter. Because people depend upon jobs to support themselves and because people need to shelter, the availability of jobs and the housing availability are important motivations for moving. The linkages back to population inhibit migration according to employment conditions and housing availability.

In this text the term housing availability very broadly denotes not only the vacancy rate in the housing stock but also other concomitants of the housing supply as rent levels, diversity of choice in size and location, and quality (Alfeld and Graham, 1976). Job availability corresponds to several job-market conditions as unemployment, job-openings, promotions and overtime. People tend to move away from areas where aggregate attractiveness is relatively unfavorable to areas where market opportunities are greater. When job-market and/or housing market conditions are relatively favorable, market conditions tend to stimulate in-migration and tend to discourage out-migration of people.

As business activity increases, the business structures availability for firms declines and the job availability increases in the urban area. For firms need accommodation, and business activity provides jobs. Because labor and accommodation are necessary inputs for most firms, the availability of labor and accommodation also influence firms' locational behavior and expansion decisions. When jobs are scarce, labor is readily available allowing business greater flexibility in choosing employees and shorting time necessary to find qualified persons to fill specific positions. Moreover, high labor availability tends to decrease wage competition for labor among firms (Alfeld and Graham, 1976). Just like an increased business structures availability for firms, an increased labor availability is an important pull factor and therefore tend to stimulate the attraction of new firms and will encourage present firms to expand.

In general, a decreased housing or business structures availability corresponds to a situation when houses or business structures are scarce. High rents, low vacancy rates, and a lack of quality housing/business structures in desirable locations all indicate that new construction is likely to be profitable. Stimulated by high demands, new housing/ business structures will be developed, which in turn increases the number of structures, as shown in Figure 1.

The bottom loops in Figure 1 show how land use by firms and by population defines the availability of land, while land acts on population and firms through housing availability and business structures availability. As an area begins to approach full land occupancy, land prices will grow and traffic congestion increases. The increasing density tends to inhibit further construction. Land supply ultimately limits urban growth. On the other hand, low land occupancy will inhibit construction also. Lack of infrastructure and lack of other kinds of facilities and utilities give the area an unattractive potential for further urban land development.

Fundamental criticism of urban dynamics

One of the most difficult parts of problem formulation is the definition of the system to be studied. Defining the system is problematically because all systems are themselves subsystems of larger systems. Where is the boundary between the system of interest and its environment best to be chosen? Traditionally, in urban dynamics it is roughly the jurisdictional boundary of an urban area that separates the system of study and the environment. Figure 2 illustrates the traditional relationship between an urban system and its environment in urban dynamics.

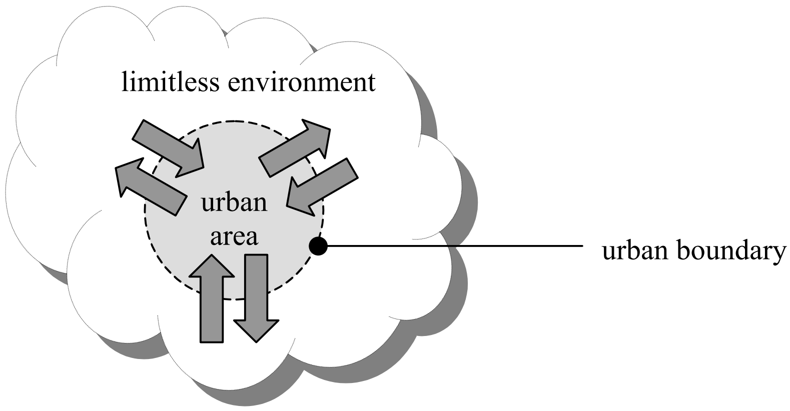

Figure 2 The urban boundary concept

Figure 2 draws on two important fundamental points of criticism, which will be discussed in this paper:

1. The problem of the 'limitless environment'
2. The 'boundary problem'

The problem of the 'limitless environment'

A first fundamental point of criticism concerns the problem of the 'limitless environment'. The traditional model boundary assumes no system-environment feedback relationships of critical importance, but cross-boundary flows such as migration or commuting are possible. The environment of an urban area is actually the rest of the universe, being the source and recipient of all cross-boundary flows. The environment is therefore limitless, in the sense that there are more potential in-migrants than the urban area can possibly contain and that potential out-migrants always succeed in moving to the system environment. The limitless environment plays also an important role in the 'boundary problem'.

The 'boundary problem'

Internally created flows as well as flows that cross the urban boundary create changes in urban conditions. Examples of internally created flows are the number of births and deaths, defined as a percentage of the population within the area. Other flows determined by internal conditions are for instance housing construction, business construction and demolition of structures.

There are also flows that cross the urban boundary, such as migration of people, migration of business (jobs) and commuting (labor force). Figure 3 illustrates how the amount of population is influenced by net migration.

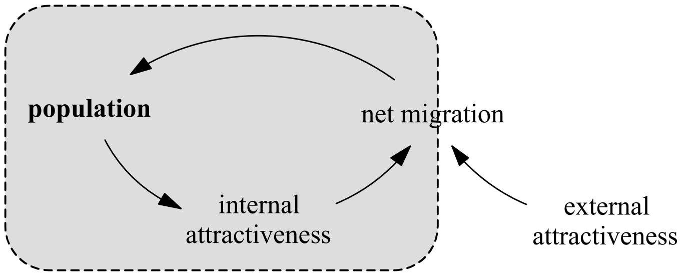

Figure 3 The concept of relative attractiveness

The attractiveness of an urban area is an important driving force regarding flows that cross the urban boundary. For modeling purposes, absolute measures of the attractiveness of the urban area are unimportant. Traditional urban dynamic models recognize only factors that differentiate the urban area from its environment (Graham, 1974). Cross-boundary flows *change* when the differences between the attractiveness of the urban area (internal attractiveness) and the attractiveness of the environment (external attractiveness) *change*. If there are no differences in attractiveness, then the normal cross-boundary flows (migration in Figure 3) take place. Any change in internal or external conditions can change the relative attractiveness of an urban area and its environment, triggering flows such as migration across the system boundary. If relative attractiveness to accommodate or/and to work in an area increases with respect to the urban environment, in-migration will increase and out-migration will decrease.

The principle of relative attractiveness is often misinterpreted and one of the most criticized fundamental principles of urban dynamics. From this point of view, it is essential to understand the idea that the urban area's environment functions as a moving reference point, with which to compare conditions within the area to govern cross-boundary flows. For this reason, a traditional urban dynamics model need not and does not consider such effects as technological change, nor does it portray explicitly the dynamics of the national economy (Graham, 1974).

Fundamental criticism exists whether the internal system interactions or external forces primarily cause socioeconomic development of an urban area. In defining the urban area and in specifying the system boundary, urban dynamics implicitly assumes that the significant behavior of an urban area is generated within the urban boundary. Traditional urban dynamics applications portray the urban area as a *self-organizing system*. But, doesn't feedback between the urban system and its environment help to explain urban behavior? Experts have questioned the self-organizing assumption of traditional urban dynamics. As the impacts of a system has on its surroundings may not be immediate and may possibly rather complex, perhaps following chains of interrelated responses in its environment may then feed back to the system itself.

The problem of drawing a system boundary so that internal elements cannot influence variables outside the system that in turn exert a significant influence on the system, is called the 'boundary problem'. Although the boundary problem depends on the goals and objectives to be studied, it is impossible to define the *perfect* system boundary. It is in a certain way impossible to define within the boundary all the dynamic structure necessary to explain and possibly cure the problem of study. However, further research into the urban boundary problem would be very useful in order to reduce the boundary critics. How can this be done? The answer seems to be as simple as it seems to be impossible: model the environment.

Spatial distribution in urban dynamics

When suburban areas or more distant rural and urban areas also define the urban system dynamically, an adequate model should represent spatial interactions between spatial subsystems explicitly. For instance, interactions between a city and its suburbs are stronger and more extensive than interactions between a city and its larger environment. An explicit subsystem representation is needed to account for migration and commuting between the central city and its suburbs, because the city and its suburbs together represent the metropolitan system.

Spatial disaggregated models can not only generate more accuracy but certainly also extend the ranges of policy issues addressed by the model. Several attempts have been made to tackle the boundary problem by simply extend existing urban models. Traditional city-suburb models contain two parallel but separate geographical sectors, each based upon structures of traditional urban dynamics models (Schroeder III, 1975). Figure 4 shows the city-suburb concept in a two-sector model.

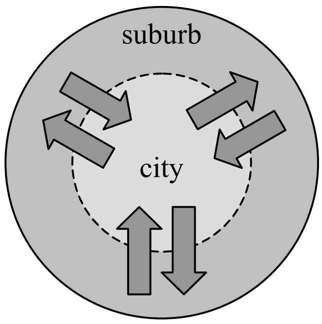

Figure 4 The city-suburb concept

Flows between the city and suburb sectors represent the 'interface', which interconnects separate sectors (city model and suburban model as shown in Figure 4). The interface takes care of the *spatial distribution* of migrants and commuters within the total system modeled.

Traditional interconnecting interfaces are quite complicated already. What if a system consists of many interacting subsystems? Under these circumstances, the city-suburb concept will not be adequate. Defining a subsystem in a web of interacting and dynamical subsystems in system dynamics is as difficult as interesting. Modeling spatial interaction is the ultimate challenge. In general, spatial distribution or sectional distribution of activities is important and of common interest among modelers. In transportation planning as well as in economic shift-share analyses and economic input-output analyses, modeling distribution of activities over time is of common interest. How can this easily be implemented in system dynamics? How can many urban areas be implemented in urban dynamics? Controlling the complexity of spatial distributions will be of vital importance.

Managing complexity: an example in system dynamics

Figure 5 shows a simple network system of eight entities (nodes). Each entity is explicitly interconnected with every other entity in the network system. Every connection between entities refers to a feedback loop. If each entity is interpreted as an urban area in a network of interacting and dynamical communities, each area defines and will be defined by conditions in every other area in the network system.

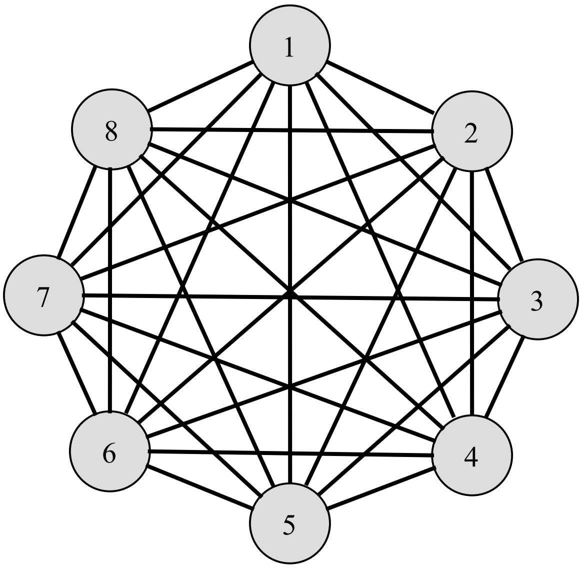

Figure 5 The network concept

Between *n* interconnected entities will be $(n^2\text{-}n)$ flows. Figure 5 shows 56 interactions ($8^2\text{-}8$), represented by 28 connections. Although this system seems to be quite simple, managing all spatial flows in system dynamics with traditional interfaces is unfeasible. This is why a new approach of modeling distribution in system dynamics is necessary, which –more in general- would make it possible to implement different kinds of interaction in system dynamics. This method will be demonstrated with an example within the field of urban dynamics. Therefore the network concept as shown in Figure 5 is considered to be a network of eight interconnected urban areas. How can these urban areas best be modeled in system dynamics?

When modeling eight urban areas, copy and paste is the most straightforward way to represent the multiple parallel urban model structures involved. Unfortunately, the associated visual complexity of the resulting model diagram can become hard to manage, both for the builder of the model and the user of the model. Arrays provide a simple yet powerful mechanism for managing this visual complexity. By "encapsulating" parallel model structures, arrays can help you to present the essence of a situation in a simple diagram (HPS, 2001).

Separate urban model structures can best be implemented in system dynamics with *one-dimensional arrays*. And how can spatial interaction between all areas be implemented in system dynamics? This is possible with *two-dimensional arrays*, as will be explained.

Modeling eight urban subsystems

In the example of Figure 5, each non-arrayed variable of a initially made visual model structure of *one* urban sector is transformed into an one-dimensional arrayed variable. The one-dimensional array's dimension is named "area". Within the dimension *area* a set of eight elements is made, named: *1*,*2*,*3*,*4*,*5*,*6*,*7*, and *8*. The equation logic for each element within the array is to be defined in generic either uniquely. In this approach, eight separate self-organizing systems are implemented in system dynamics, visualized in one simple model diagram.

Modeling spatial interactions

Between eight urban areas, as mentioned before, 56 interacting flows must be taken into account. For instance, people tend to migrate from one area to another if opportunities are expected to be better in another area. In this example, all possible households' movements can be summed in a matrix, as shown in Figure 7. Diagonal elements excepted, all elements in this matrix correspond to aggregated spatial interaction or distribution (in this case migration). Two important questions are how to define the equation logic of migration and how to implement this logic in system dynamics.

The separate urban sectors (*1*,*2*,...*8*) describe migration in response to relative attractiveness of the urban area compared with its external environment. Migration, in turn, influences the composite attractiveness of the urban area for further migration. In the example illustrated, the external environment of each urban area exists of seven other urban areas, all dynamically related. How can these complex relationships be managed?

Spatial distribution of migrants can be managed by implementing classical gravity models into system dynamics. Gravity models are frequently employed in demography and economics. Gravity models of migration assume that the flow of migrants between two locations is proportional to the product of opportunities in both locations and is inversely proportional to the distance between these locations raised to a decay power.

Mathematically, a simple relation of migration is analogous to the law of gravity:

$$F_{ij} = f\left\{P_i, O_j, D_{ij}, \beta\right\}, \text{ for example: } F_{ij} = \frac{P_i O_j}{D_{ij}^{\beta}} \quad (1)$$

Where:

F_{ij} = flow of migration between area *i* and area *j*
P_i = population of area *i*
O_j = opportunities of area *j*
D_{ij} = distance between area *i* and area *j*
β = decay of distance

If O_i in equation 1 represents a variable of production (such as total population) of area *i,* and if O_j represents the attractiveness of an area *j* (such as available houses or available jobs), the gravity model depicts all households' movements. The gravity model assumes that most movements have destinations within the area of origin. Real migration depends of destination area's attractiveness and its accessibility. An attractive area *i* nearby other areas *j* with less favorable conditions will attract many people, which in turn influences the attractiveness of area *i*.

Urban changes can occur as a result of changes in both endogenous and exogenous regional levels. As the gravity model functions as the interface between self-organizing urban subsystems, urban interaction may affect the behavior and response of the whole system. The network feedback idea is visualized in Figure 6. Figure 6 illustrates that all elements are affecting each other *simultaneously* in time and space.

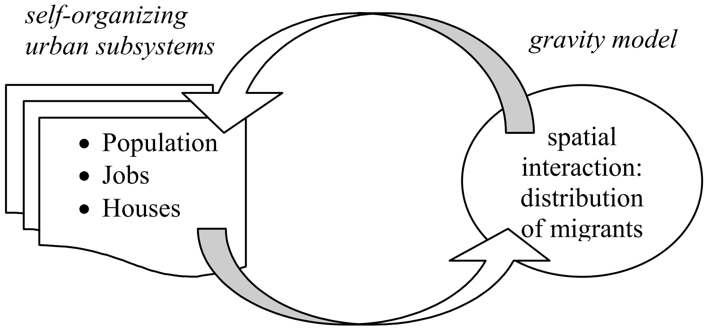

Figure 6 Simultaneous interurban feedback process

Equation 1 shows just a simple gravity model with a lot of drawbacks and limitations. However, the correctness of the gravity model is not the major issue in this chapter. The main goal of this chapter is to show how to implement a gravity model into system dynamics.

As every variable with two indices correspond to a matrix, calculating with a gravity model is nothing more then calculating with matrices. The gravity model of equation 1 contains two matrices: matrix D (with all distances) and matrix F (with all migration flows). Matrix F, with all origin-destination flows F_{ij}, is visualized in Figure 7.

FLOWS		*to area j*							
		1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
from area i	*1*	..	..	..	..	..	..	..	..
	2	..	..	..	..	..	..	..	..
	3	..	..	..	..	..	..	..	..
	4	..	..	..	..	..	..	..	..
	5	..	..	..	..	..	..	..	..
	6	..	..	..	..	..	..	..	..
	7	..	..	..	..	..	..	..	..
	8	..	..	..	..	..	..	..	..

$$\sum_j = arraysum(i,*)$$

$$\sum_i = arraysum(*,j)$$

Figure 7 Distribution matrix

As two-dimensional arrays have to be interpreted as matrices when written on paper, all calculations with two-indices-variables can be implemented in system dynamics by two-dimensional arrays. Therefore, the general argument discussed in this paper is that every matrix-based calculation (either spatial or sectional) can be implemented in system dynamics simply by two-dimensional arrays.

The gravity model as shown in equation 1 exists of exactly 5 variables: F_{ij}, P_i, O_j, D_{ij} and parameter β. All variables have to be implemented in system dynamics software, for instance STELLA®. Where β is an universal parameter, D_{ij} is a matrix containing unique internally distances and unique interurban distances. Variables P_i and O_j correspond to variables as defined in each urban sector. For instance, variable O_j refers to available jobs or available houses in area j. Finally, matrix F_{ij} gives the migration flows, which in turn influence the self-organizing urban areas. Figure 8 shows a system dynamics diagram of the gravity model. Numbers in Figure 8 correspond to generic logic, which will be explained.

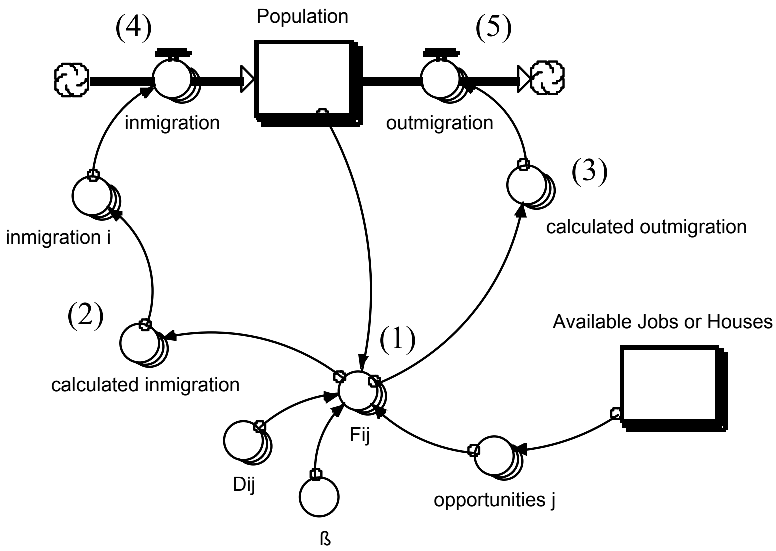

Figure 8 Spatial interaction diagrammed in system dynamics

Although the network system is quite complex, its diagram remains visually remarkable simple and manageable. However, the complexity of the overall system remains unchanged. Visually can't be seen how many subsystems are defined, but there may be over a hundred! By examining variables' dimension and set of elements, the system's complexity can be estimated. It is clear though that both the builder and the user of the model are supposed to have good understanding of the system as a whole and need to have a good interpretation of arrays. If so, many possibilities will arise.

While defining variables into system dynamics, the big challenge is to avoid invertible arrays. Moreover, creative avoiding and 'fooling' of arrays is absolutely necessary to succeed in implementing spatial or sectional complexity in easy-to-use system dynamics software.

Figure 8 shows how variables of urban model structures are input for the gravity model. The urban model structures represent different rates of flows that cause system levels to change. In the example visualized, the urban model structures are made by transforming variables of one initially made urban model structure into one-arrayed variables with dimension name i. Eight elements are made within dimension name i. Population, available jobs and houses are calculated uniquely for eight urban sectors.

Both population and available houses or jobs are levels that are inputs for the gravity model, but they have a different dimension. As equation 1 shows the calculation of F_{ij}, the population P is dimensioned i while the opportunities O are dimensioned j. In other words: people in urban area i look at opportunities in every area j. However, all levels of the urban model structure are dimensioned i. The level of population is dimensioned *i* already. The levels of opportunities, however, which are dimensioned *i*, will have to be transformed in variables dimensioned *j*. Therefore, Figure 8 shows a new variable ‘opportunities j’, which is dimensioned *j*, with all elements defined manually. The matching transformation process in order to avoid invertible arrays is visualized in Figure 9.

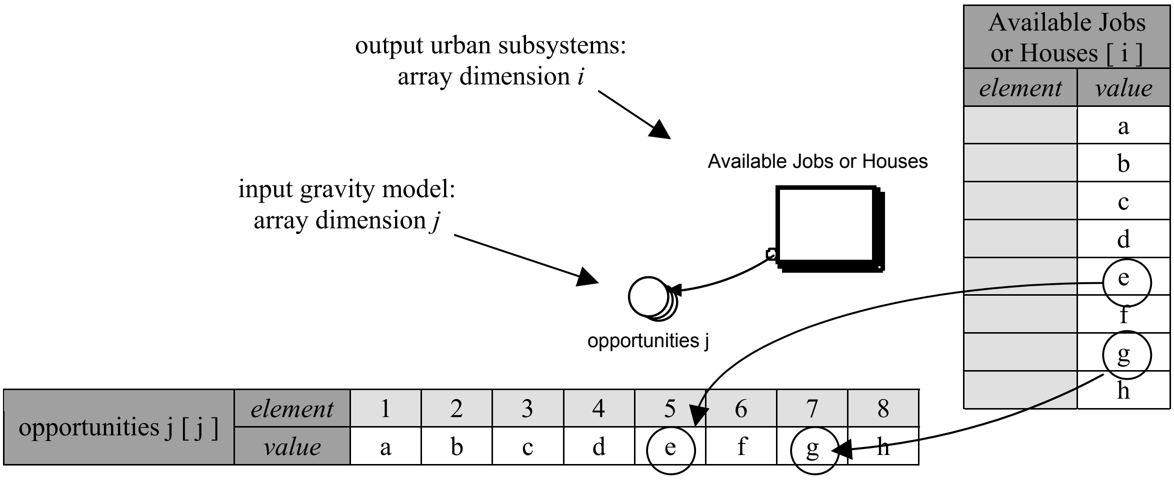

Figure 9 Manually transformation process of arrays

Imagine dimension *i* as rows and think of dimension *j* as columns, as shown in Figure 7. Note that the transformation process of arrays is a manual task. Every row-element in the variable of origin (dimensioned *i*) has to be linked manually into the referring column-element in the variable of destination (dimensioned *j*), as Figure 9 shows.

Matrices F_{ij} and D_{ij} are implemented as double-arrayed variables with dimension *i* (rows) and dimension *j* (columns), as to be matrices interpreted as in Figure 7. After D_{ij} is defined with real data-characteristics and parameter β is estimated, the generic logic of the gravity model (equation 1) can be defined in variable F_{ij}:

$$(Population[i]*opportunities\_j[j])/Dij[i,j]^\wedge ß \quad (1)$$

As shown in Figure 7, column summation over eight rows (minus internal migration) defines the amount of in-migrants of destination area *j*, who move out of other areas of origin *i* present in the network system (7 other areas). Row summation over eight columns (minus internal migration) defines the total number out-migrants of area of origin *i*, descended from other seven areas of destination *j*. These summations can be made by the “arraysum-command”, which are made in the auxiliaries ‘calculated inmigration’ and ‘calculated outmigration’ (Figure 8). The amount of in-migrants and out-migrants have to be manually corrected for each area by diminishing the array summations with the amount of internal movements. For example, the *calculated* amount of in-migrants and out-migrants of area 5 are defined respectively:

$$ARRAYSUM(Fij[*,5])-Fij[5,5] \quad (2)$$

$$ARRAYSUM(Fij[5,*])-Fij[5,5] \quad (3)$$

In making it possible defining these calculations, invertible arrays must be avoided. That is why the variable in which the arraysum-calculation is made must have the same dimension as the dimension that is *not* summed within the calculation. Therefore, the variable 'calculated inmigration' is dimensioned *j*. However, the feedback loop as shown in Figure 6 is just complete when the calculated amounts of migrants define the migration flows in the urban model structures. As these urban model structures are dimensioned *i*, calculated in-migration has to be transformed into a variable dimensioned *i*. Therefore i-dimensioned variable 'inmigration i' is made, which is defined manually in a similar procedure as visualized in Figure 9, transforming in-migration in an appropriate dimension.

Finally, in-migration flows and out-migration flows are defined with generic logic, respectively:

$$\text{inmigration\_i[i]} \tag{4}$$

$$\text{calculated\_outmigration[i]} \tag{5}$$

A case study of Dutch spatial development

The network-concept illustrated is applicable to different kinds of systems in social and economic science. In urban planning, complexity theory can be applied to a city and its suburbs as well as to regional subsystems. The principle of multiple interacting self-organizing systems has recently been applied in a large case study of The Netherlands.

The Dutch case study made is an attempt to understand spatial developments of Dutch regions. For this, driving forces of regional developments are studied. This study, initiated at Delft University of Technology at the department of Civil Engineering, has an underlying goal in surveying the regional impacts of large infrastructure measures.

As it is widely accepted that transportation defines spatial development, planners of infrastructure are very interested in the indirect spatial effects of infrastructure measures. Moreover, large infrastructure investments aim at indirect spatial effects. At this time Dutch politics investigate a very large investment in infrastructure. This appealing project concerns realization of extremely fast and expensive railway infrastructure ('Transrapid') in the West of The Netherlands, as will be explained. In order to understand this project's regional impacts, driving forces of regional changes are captured in system dynamics (STELLA®).

40 Dutch regions

In order to understand spatial development of regions, the most important interrelationships between economic and demographic aspects are of interest. Several major internal forces control the balances of population, housing and firms within an urban area. These forces go with several markets that can be distinguished, such as the housing market, labor market and market for business structures. On the national level, each market is segmented spatially as each market consists of a large number of submarkets that are more or less independent of each other and, therefore, between which interaction is limited. Neglect of this spatial segmentation leads to an inappropriate understanding of markets phenomena (Rietveld, 1984). Therefore, the regional dimension can best study market changes. The question rises, which is the best spatial scale to describe regional economics and demographics.

As a department of the Ministry of Economic Affairs, *Statistics Netherlands* collects statistics of different regional classifications. Statistics Netherlands distinguishes four important regional classifications, which are: land parts (4), provinces (12), Corop-regions (40), and municipalities (537). The statistical Corop-regions, designed in the early seventies, originally account for self-organizing functional relationships within the urban area as interregional flows such as migration and commuting are minimal. The 40 Corop-regions (Figure 10), therefore, integrate statistics used in urban planning and socioeconomic planning. From a traditional point of view, the Corop-boundary would be the best Dutch urban boundary in regional analysis. Therefore, the Corop-regions have been applied in the Dutch case.

Figure 10 The Netherlands divided into 40 counties
(source: Statistics Netherlands)

Although the Corop-classification and its regional socioeconomic processes are more or less independent of each other originally, interactions between Corop-regions have intensified during history. Changes in regional attractiveness, due by changes in regional accessibility amongst other developments, have intensified interregional flows such as migration and commuting. Hence, in understanding regional change and indirect spatial effects of infrastructure, interregional flows must be taken into account.

Case model overview

In capturing mechanisms underlying long-term evolution of urban areas, different markets can be distinguished, as shown in Figure 11. Labor force and firms are confronted with each other at the *labor market*; people seek for housing at the *housing market* and firms seek for accommodation at the *market for business structures*. Demography of *people* as well as demography of *firms* are distinguished, which are described by demographic concepts of birth, death and relocation. Principles of relocation modeled are (1) internal migration of *people* due to labor market conditions, (2) internal migration of *people* due to housing market conditions, (3) internal migration of *firms*, and (4) internal *commuting*, as illustrated in Figure 12. Urban stakeholders' behavior defines urban attractiveness and finally defines changes in urban *land use*.

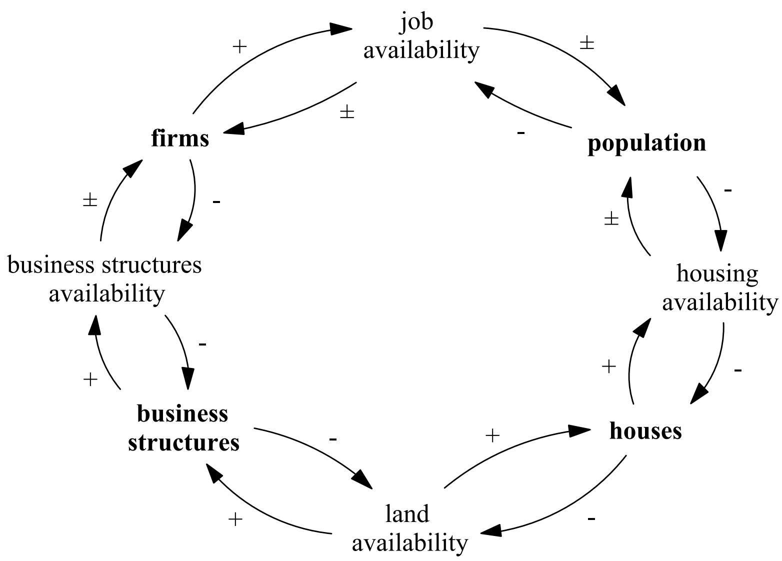

Figure 11 Renewed overall urban interactions

In this case, for a national centralized region (region 'Utrecht' for instance, as defined by Corop 17 in Figure 10) the 'problem of the urban boundary' as well as the 'problem of the limitless environment' are strongly reduced. Hence, the approach applied improves traditional urban dynamics approaches fundamentally.

Therefore, urban network analysis needs adjustment of fundamental principles of urban dynamics. Especially the principle of relative attractiveness has to be renewed compared with traditional approaches. Because on the Corop-level the Dutch environment is modeled also, interaction with the limitless environment concerns only cross-country flows such as immigration of foreigners and emigration to other countries. Although cross-country flows of migration of people, cross-country migration of firms, and cross-country commuting are modeled as in traditional urban dynamics, cross-country flows are not significant with respect to nationally internal flows and therefore do not detract the model from its renewed theoretical fundament.

Dutch internal flows are not only initiated within a closed system, flows within this system are triggered by literal comparison of market conditions. An attractive region's power of attraction of migrants depends of other regions' attractiveness. If other regions are far more attractive, another –but less- attractive region's net migration could even decline. While the traditional concept of relative attractiveness is abstract, the renewed principle of relative attractiveness is far more real. The renewed principle of relative attractiveness is the exponent of the increased complexity of the urban dynamics model. The renewed overall causal-loop diagram in Figure 11 illustrates the increased complexity of urban dynamics, as it has been applied in the Dutch case.

The renewed principle of relative attractiveness concerns cross-boundary flows at regional level. As can be derived from Figure 11, interregional migrations of people as well as migration of firms and commuting are being calculated uniquely for every DT, simultaneously with other self-organizing urban processes. In other words, 1600 flows of migration of people, 1600 flows of migration of firms and 1600 flows of commuting are taken into account as the system moves from one state to another, influencing many self-organizing systems, which in turn influence spatial distributions again. As illustrated in Figure 12, gravity models apply all spatial interactions.

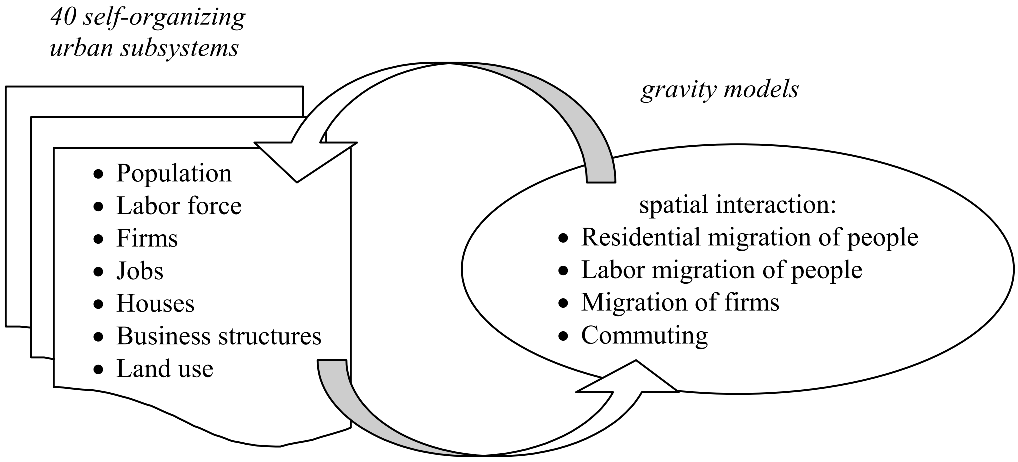

Figure 12 Overview developed model structure

Interconnecting 40 urban models requires many entities in the software. As every double-arrayed variable consists of 40 rows and 40 columns, every double-arrayed variable consists of 1600 entities. As the amount of entities in the software is limited, the model structure is made only as complicated as necessary. Moreover, a large network model, by definition, has a broader focus than a traditional urban dynamics model. Accordingly, neither sector of the network model need be as detailed as traditional urban dynamics models. Hence, each urban sector is based upon an aggregated urban dynamics model structure containing only a few levels, as shown in Figure 12. Every urban sector of the network model should be fully consistent in behavior with the traditional urban dynamics model though, but they operate at a higher level of aggregation. The final causal-loop diagram of each urban sector is illustrated in Figure 13. In fact, the total model developed exists of 40 causal-loop diagrams as shown in Figure 13, all applied in one STELLA® model.

The case-model shows non-linear microscopic interactions that give rise to macroscopic states of behavior. To understand this behavior, the interregional processes' theory must be clear. Because internal migration as well as internal commuting is modeled, people (and therefore houses) and firms (and therefore jobs and business structures) will relocate over regions in time. In extreme cases, functions can drive out others, influencing distribution of socioeconomic functions eventually.

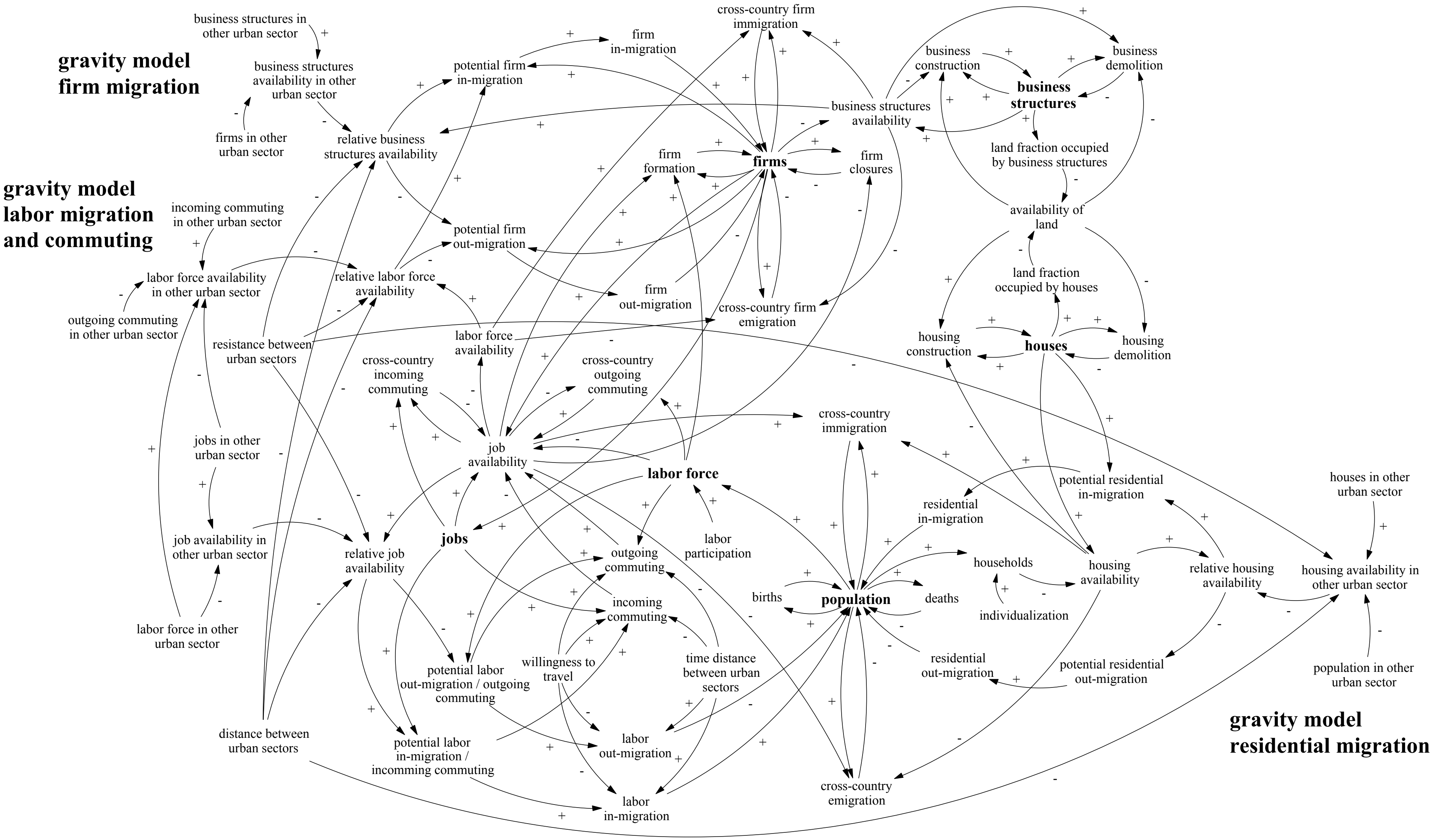

Figure 13 Urban dynamics case

Interurban migration of people and commuting

Migration of population and commuting are closely related in reality as well as in the model developed. As commuting is an alternative for migrating, an adequate approach will have to take this interdependency into account. Therefore, migration is segmented according to motivation. The model explicitly distinguishes migration due to housing market conditions (residential migration) and migration due to labor market conditions (labor migration). Only the latter is coherent with commuting in an aggregate approach. This chapter only discusses migration due to labor market conditions and its relation with commuting, because this defines -and makes it possible to study- spatial distribution of population (houses) and jobs (business) in essence.

Model's gravity formulation involving labor migration and commuting show how many people from every area occupy jobs in their own area and in other areas. Mathematically, the gravity model applied depicts how many people of area *i* occupy jobs in areas *j*. Therefore, distribution of labor force of region *i* over jobs in regions *j* depends of:

- Labor market attractiveness of region *i*
- Labor market attractiveness of other regions *j*
- Accessibility of region *j* in terms of time, money and trouble

Whether people commute or migrate due to labor market conditions, is defined by travel time distance between areas in an aggregate approach. These relationships are visualized in Figure 14 and Figure 15. The causal-loop diagram of Figure 14 shows how labor in-migration and incoming commuting of every region is defined. Figure 15 shows the way labor out-migration and outgoing commuting is defined. Actually, these Figures are visual illustrations of the gravity model used.

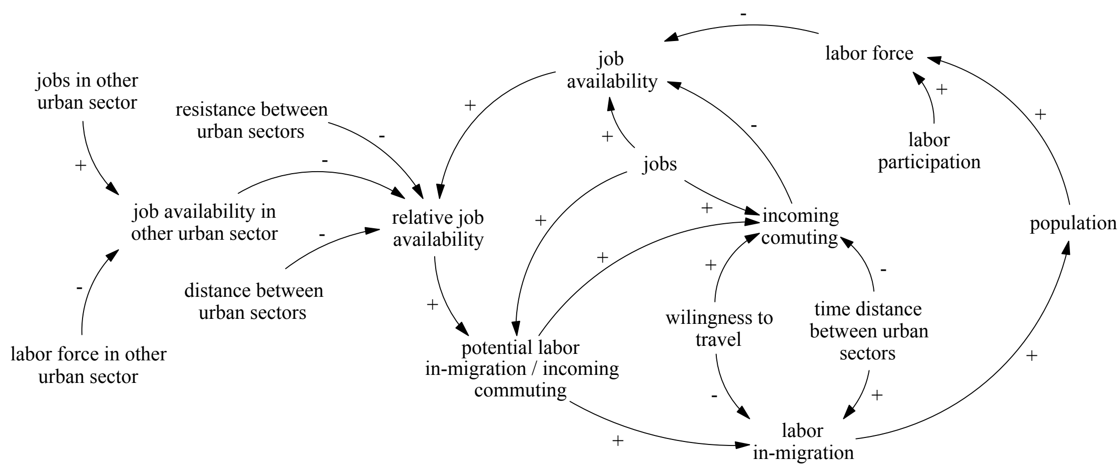

Figure 14 Urban labor-in-migration and incoming commuting

As Figure 14 and 15 show, the gravity model applied is quite complex in its causal relationships. The mathematical definition of the gravity model, however, still is manageable and gives perhaps a more comprehendible insight of the processes defined.

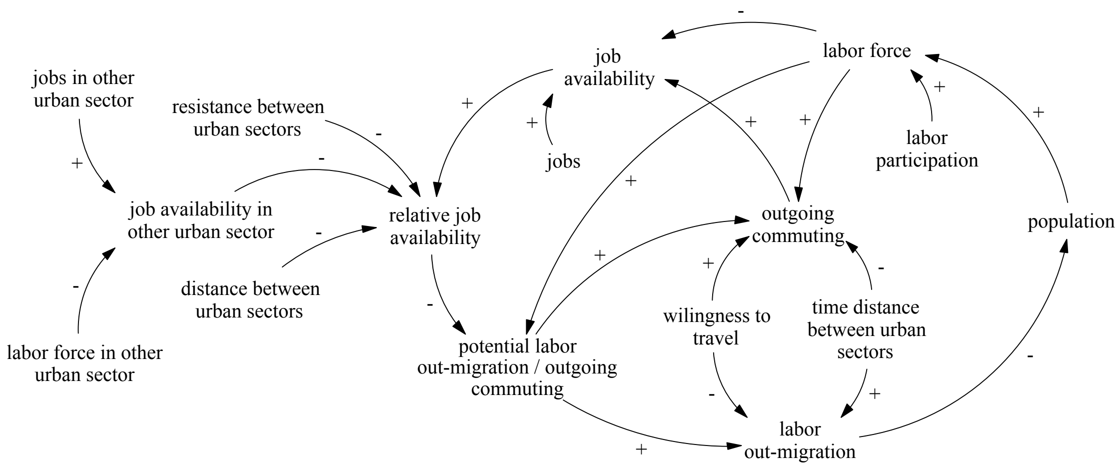

Figure 15 Urban labor-out-migration and outgoing commuting

Social sciences distinguish within the decision-making process of migration two important phases: (1) the desire to migrate and (2) the destination of migration. Theoretically, people's desire to migrate and their possible destination are closely related as the presence of alternatives of destination plays an important role in the desire to migrate. When people want to migrate, but other areas do not seem to inhibit more opportunities, potential migrants do not migrate after all. To apply this process in urban dynamics, the phenomenon of 'potential migration' has been taken into account.

First, a regions' amount of people occupying jobs in other Dutch regions (*pot-OUTLF*) is estimated (referring to 'potential-phenomenon') with a push factor of *internal* employment conditions, as shown in equation 6. If these people really occupy jobs in other regions still isn't defined, as will be explained.

$$pot\_OUTLF_i = Laborforce_i * pct\_OUTLF_i * AJM\_OUTLF_i \qquad (6)$$

Where:

pot_OUTLF_i = potential amount of labor force of region *i* that occupy jobs in other Dutch regions, based on internal employment conditions in region *i*

$Laborforce_i$ = living labor force in region *i*

pct_OUTLF_i = percentage of living labor force in region *i* that occupy jobs in other Dutch regions, based on normal employment conditions in region *i*

AJM_OUTLF_i = attractiveness-of-jobs multiplier, which is a push factor regarding interregional job occupancy based on employment conditions in region *i*

The coefficient *pct-OUTLF* defines a proportional relationship between the amount of living labor force in an area and the amount of people in this labor force that occupy jobs in other Dutch areas. Hence, a large labor force is assumed to generate possibly large migration and/or commuting. Moreover, the percentage *pct-OUTLF* is differentiated regionally, which takes account of different kinds of discrepancies in regional labor markets (for instance, an area's character of business).

The attractiveness-of-jobs multiplier *AJM_OUTLF* modulates the rate of potential out-migration and outgoing commuting in response to internal employment conditions. This multiplier is defined in a multiplier table, as shown in Figure 16. When the labor-force-to-job-ratio *LFJR* equals 1.0, employment conditions are supposed to be 'normal', and the 'normal' out-migration and outgoing commuting takes place as defined by equation 6 and the value of *AJM_OUTLF*.

The used ratio *LFJR* in Figure 16 represents a surrogate measure of many aspects of internal employment conditions (Alfeld and Graham, 1976). Dividing the number of persons in the labor force by the number of jobs gives the labor-force-to-job-ratio. An *LFJR* value greater than 1.0 gives unfavorable employment conditions (a surplus of labor over jobs) relative to normal conditions. Inversely, a value less than 1.0 indicates favorable employment conditions relative to a normal period. When employment conditions are not normal, the labor force may not correspond precisely to the actual number of people seeking work, and jobs may not correspond precisely to the actual number of employment positions in the urban sector. Consequently, the LFJR bears no simple quantitative relationship to actual employment rates, as unemployment is only one possible symptom of unfavorable employment conditions; other possible manifestations of unfavorable employment conditions include low wages, reduced overtime, a lack of promotions, slow hiring rates, and layoffs.

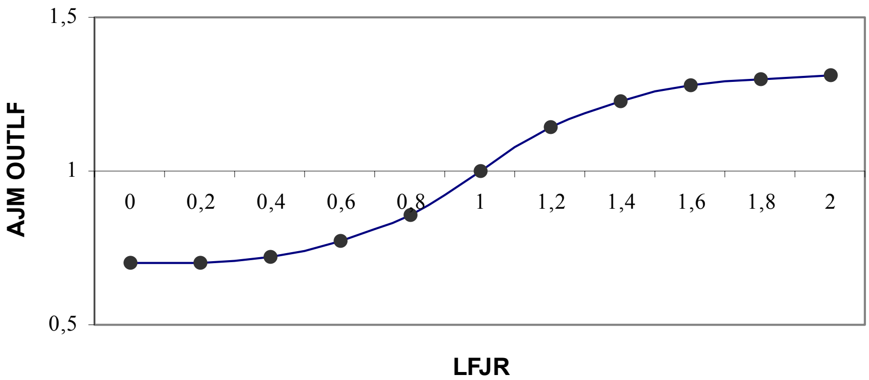

Figure 16 Attractiveness-of-jobs multiplier table *AJM_OUTLF*

As shown in Figure 16, unfavorable labor market conditions (indicated by a value of *LFJR* greater than 1.0) stimulate potential labor out-migration (indicated by a value of *AJM_OUTLF* greater than 1.0). the left side of the attractiveness-to-jobs multiplier table depicts favorable employment conditions, representing the hypothesis that job conditions are good and less people potentially tend to migrate or commute to an other area.

The question rises how many people really occupy jobs outside the area, how many people will commute, and how many people finally migrate due to labor market conditions. Therefore, a gravity-model depicts all possible flows of labor between 40 Corop-regions. The distribution of labor-migrants and commuters of an area *i* over areas *j* is defined by '*indices of accessibility*' and '*potentials of accessibility*'.

A first estimation of potential labor-in-migrants and incoming commuting (*pot-INLF*) of an area *j*, is derived from a pull factor of urban employment conditions in urban sector *j* (equation 7). An attractiveness-of-jobs multiplier AJM_INLF represents this pull factor, which is actually the *inverse* of Figure 16. Hence, under favorable employment conditions the attractiveness-of-jobs multiplier *AJM_INLF* rises above 1.0 and stimulates the rate of potential in-migration and potential incoming commuting. When the labor-force-to-job ratio *LFJR* rises above 1.0, job conditions worsen and potential in-migration and potential incoming commuting will decline. As equation 7 defines, potential labor-in-migration and incoming commuting depend of the amount of jobs in urban sector *j*, as every job is a potential opportunity for migrating or commuting. The percentage *pct-INLF*, regionally differentiated due to different kinds of discrepancies in regional labor markets, defines potential labor in-migration and potential incoming commuting under normal employment conditions in urban area *j*.

$$pot\_INLF_j = Jobs_j * pct\_INLF_j * AJM\_INLF_j \quad (7)$$

Where:

pot_INLF_j	= potential amount of in-migrants or incoming commuters of region *j* based on internal employment conditions in region *j*
$Jobs_j$	= amount of jobs in region *j*
pct_INLF_j	= measure of pull of potential labor in-migrants or incoming commuting of region *j*, based on normal employment conditions in region *j*
AJM_INLF_j	= attractiveness-of-jobs multiplier, which is a pull factor regarding labor in-migrants and incoming commuting, based on employment conditions in region *j*

The amount of people in area *i* who actually occupy jobs in regions *j* depends of acquaintance with region *j* and employment conditions of region *j* relative to other potential regions of destination. Distance is an sophisticated factor in the process of migration and commuting. People are most familiar with local job market conditions and people are likely to have friends and relatives in the neighborhood that can pass along information about job opportunities within areas nearby. As people don’t give up their social life easily, keep motives result in relatively much commuting over short distances and labor migration over long distances. This phenomenon is described by *distance decay*, as illustrated in Figure 17.

Figure 17 also illustrates that discontent about present living standards, possibly resulting in migration or commuting, can be triggered by changing labor market attractiveness between urban sectors as employment conditions in people’s present area change or/and employment conditions in alternative areas change.

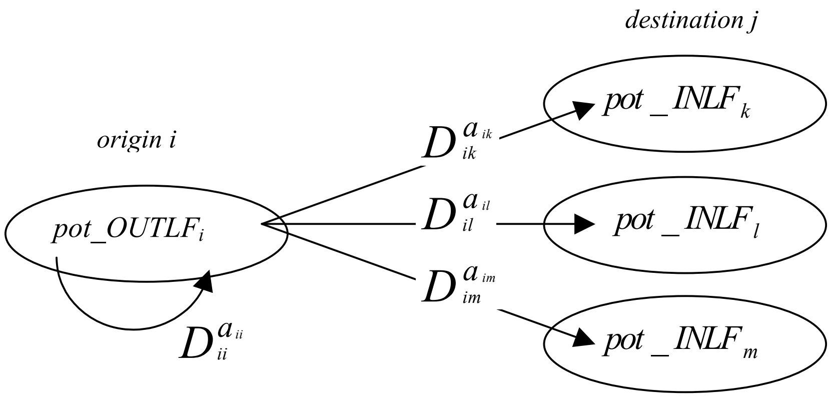

Figure 17 Derivation gravity model of labor migration and commuting

In mathematically defining the phenomenon illustrated in Figure 17, attractiveness's of regions of destination *j* -for labor out-migrants or outgoing commuters of region *i*- are defined by *indices of accessibility* (*BI_LFMC*). Variable BI_LFMC_{ij} describes the accessibility of inmigration's/incommuting's attractiveness of potential regions of destination *j* for people of origin *i*, as defined in equation 8. Further, the value of P_LFMC_i defines the accessibility of a region's environment for potential out-migrants and outgoing commuters of region *i* (equation 9).

$$BI\_LFMC_{ij} = \frac{pot\_INLF_j}{D_{ij}^{b_{ij}}} * cfactor\_LFMC_{ij} \quad (8)$$

$$P\_LFMC_i = \sum_j BI\_LFMC_{ij} = \sum_j \frac{pot\_INLF_j}{D_{ij}^{b_{ij}}} \quad (9)$$

Where:

BI_LFMC_{ij}	= index of accessibility for labor migration and commuting from region *i* to region *j*
pot_INLF_j	= potential amount of in-migrants or incoming commuters of region *j*, based on internal employment conditions in region *j*
D_{ij}	= average time traveling distance between region *i* and region *j* (measure of acquaintance with region *j* for people in region *i*
b_{ij}	= decay power of D_{ij} (time, money and trouble of distance)
$cfactor\_LFMC_{ij}$	= factor that corrects correction labor flows from region *i* to region *j*, which takes account of attractiveness of employment conditions in region *i* relative to employment conditions in region *j*
P_LFMC_i	= potential of accessibility for labor out-migration or outgoing commuting of region *i*

Multiplier table $cfactor\_LFMC_{ij}$ modulates the complex relationship between the *desire* to migrate or commute and *real* migration or commuting. Multiplier table $cfactor\_LFMC_{ij}$ shows the difference between labor market attractiveness between two regions, as shown in Figure 18. Therefore, a region's Dutch environment truly exists of moving reference points.

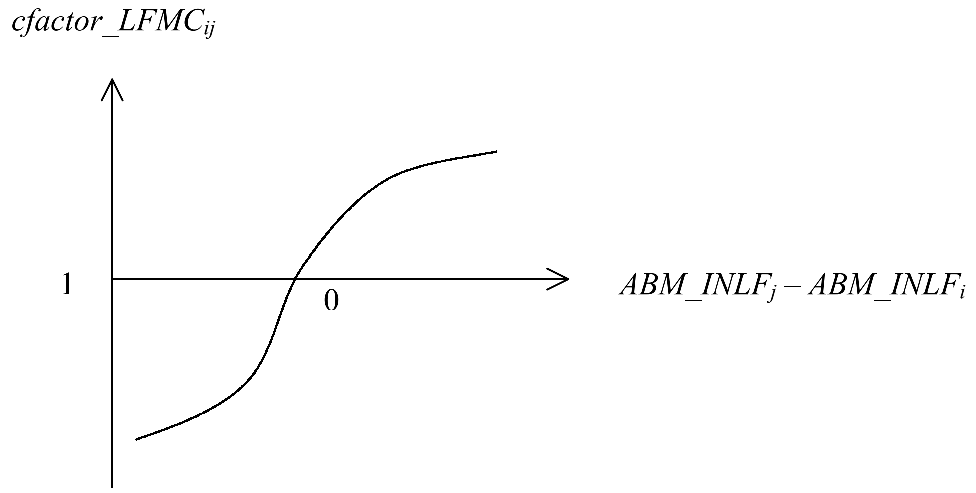

Figure 18 Multiplier table $cfactor\_LFMC_{ij}$

If employment conditions are unfavorable in region *i*, more people (relative to normal employment conditions) want to occupy jobs in other regions based on *internal* labor market conditions. But if employment conditions in other Dutch areas are unfavorable also, perhaps not so many people want to occupy jobs in other regions after all. Multiplier table $cfactor\_LFMC_{ij}$ modulates this phenomenon by affecting the values of indices of accessibility BI_LFMC_{ij} (equation 8). If employment conditions in other areas are even far more unfavorable, employment conditions in region *i* will be *relatively* favorable and an increasing labor migration and/or incoming commuting is to be expected. The value of *P_LFMC* of this relatively favorable region will then be relatively large with respect to other values of *P_LFMC*, as all indices of accessibility *BI_LFMC* from *i* to *j* are stimulated. Finally, this will increase labor migration and/or more incoming commuting, as migration and commuting are distributed by the relative value of P_LFMC_i in the sum of all values of P_LFMC_i (equation 10). This illustrates how multiplier table $cfactor\_LFMC_{ij}$ regulates pull and push forces underlying labor-migration and commuting.

If employment conditions seem to be favorable based on internal labor market conditions, but other urban areas are even more favorable, people will be relatively unsatisfied. The pull forces of other regions will attract migration and commuting through by which many people want to occupy jobs in the area's environment after all. In this case, multiplier table $cfactor\_LFMC_{ij}$ will decline the particular value of P_LFMC_i (because all indices of accessibility *BI_LFMC* from *i* to *j* are declined), and will stimulate labor out-migration and outgoing commuting eventually (equation 10).

Equation 10 defines the actual distribution for which the gravity model is designed originally. Equation 10 regulates the distribution of interregional job occupancy by the relative value of P_LFMC_i in the sum of all values of P_LFMC_i. As can be derived from equation 10, a network's central urban sector with relatively favorable employment conditions will attract many labor migrants and commuters. This, in turn, will influence employment conditions in this urban sector and will eventually decrease in-migration and incoming commuting, modulated by a decreased relative value of *P_LFMC*. By this, the gravity model functions as interface between 40 regions.

$$LFMC_{ij} = pot\_OUTLF_i * \frac{BI\_LFMC_{ij}}{P\_LFBMC_i} \quad (10)$$

Where:

$LFMC_{ij}$	= direction of job occupation of labor force, based on relative employment conditions
pot_OUTLF_i	= potential amount of labor force of region *i* that occupy jobs in other Dutch regions, based on internal employment conditions in region *i*
BI_LFMC_{ij}	= index of accessibility for labor migration and commuting from region *i* to region *j*
P_LFMC_i	= potential of accessibility for labor out-migration or outgoing commuting of region *i*

People who occupy jobs outside their area of living have two options. They either commute (then travel from their area of origin/living to their area of destination/work), or they will migrate due to employment conditions. Therefore, the value of $LFMC_{ij}$ exists of two components: commuters ($Commuters_{ij}$) and migrants (LFM_{ij}). People of region *i* who are not willing to commute to their work in an other urban sector, migrate due to employment conditions in the model developed. When travel time distance is little, many people will commute. However, even when travel time distance is little, some people will migrate due to employment conditions, as job occupancy is coupled with upward socioeconomic positions sometimes. As people get a better job, they sometimes may allow a house more expensive. Therefore, migration due to employment conditions over short distances always exists. However, if travel time distance between two regions is very large, not only few people will occupy jobs in that other region, but also few will travel between these regions as they will migrate.

The amount of interurban commuters in every direction between region *i* and region *j* is estimated with multiplier table $pct\_Commuting_{ij}$, as defined in equation 11.

$$Commuting_{ij} = LFMC_{ij} * pct\_Commuting_{ij} \quad (11)$$

Where:

$Commuting_{ij}$	= amount of commuters of region *i* to region *j*
$LFMC_{ij}$	= direction of job occupation of labor force, based on relative employment conditions
$pct\_Commuting_{ij}$	= percentage of labor force in region *i*, who work in region *j* and still live in region *i*

Multiplier table $pct\_Commuting_{ij}$ modulates people's behavior regarding travel time distance in an aggregate way. Living far from work and working far from home are phenomena modulated by the principle of Figure 19.

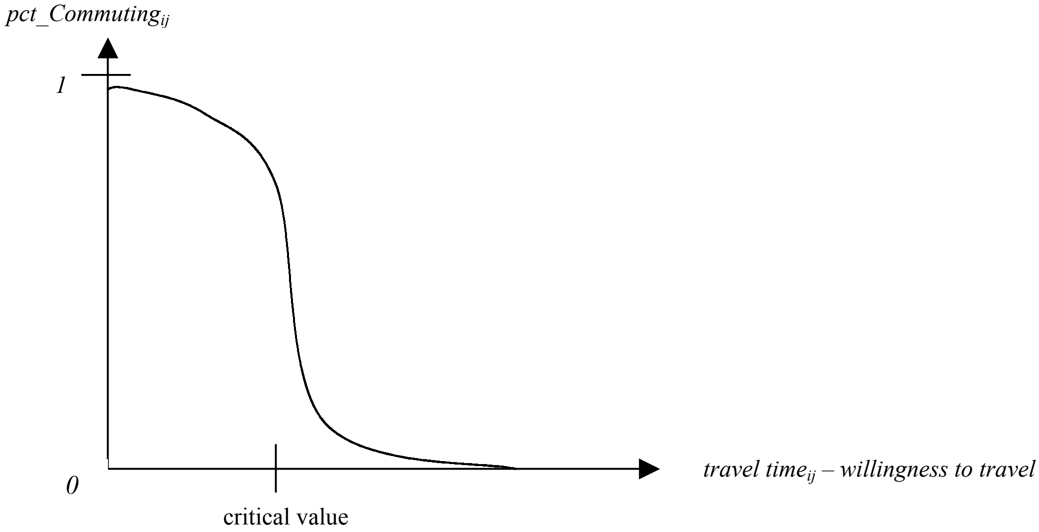

Figure 19 Aggregate estimation of commuting in interurban labor flows

As Figure 19 shows, the x-axis contains two elements: (1) travel time distance, and (2) willingness to travel (with respect to commuting). Together they define the value of $pct\_Commuting_{ij}$. For instance, when (average) travel time between two urban sectors is approximately 15 minutes, while people have a willingness to travel of about 30 minutes, many people who occupy jobs in that particular other region are assumed to commute. Because people do not have a problem with this traveling time, many people will commute as $pct\_Commuting_{ij}$ is nearly one. As mentioned before, however, some labor migration will exist, defined by the function not fully be 1 if (*travel time*$_{ij}$–*willingness to travel*) equals 0. As (exaggerated) illustrated in Figure 19, a critical value of (*travel time*$_{ij}$–*willingness to travel*) will result in a fast decrease of commuting, as less people are willing to commute between regions.

Furthermore, the model posses universal trends in both *travel time*$_{ij}$ and *willingness to travel*, which in reality are variables that change in time. Technological developments in the supply of transportation systems, among which faster conveyances and infrastructure improvements, have lead to declining travel times. Willingness to travel has changed due to changing willingness to pay for transportation costs, in terms of budget, time and comfort.

After all commuting flows between regions are defined by equation 11, total incoming commuting (INC_j) and outgoing commuting ($OUTC_i$) can be derived from variable $Commuting_{ij}$. Equation 12 and equation 13 show how total incoming commuting INC_j and outgoing commuting $OUTC_i$ are calculated. The principle of these calculations has already been shown in Figure 7. Column summations and row summations, reduced by internal flows of labor force, give final outgoing commuting and final incoming commuting of each urban sector. Equation 12 shows outgoing commuters of every urban sector of origin *i* who work in other urban sectors *j*. Equation 13 shows that in every urban sector of destination *j*, commuters can possibly be expected from all other Dutch urban sectors.

$$OUTC_i = \sum_j Commuting_{ij} - Commuting_{i=j} \qquad (12)$$

$$INC_j = \sum_i Commuting_{ij} - Commuting_{i=j} \quad (13)$$

Where:

$OUTC_i$	= outgoing commuters of region *i*, based on relative employment conditions
INC_i	= incoming commuters of region *j*, based on relative employment conditions
$Commuting_{ij}$	= amount of commuters of region *i* to region *j*
$Commuting_{i=j}$	= amount of potential commuters who do not work in an other region

People who occupy jobs in other regions, but who do not commute, will migrate due to employment conditions. The direction and amount of labor migrants is defined by equation 14.

$$LFM_{ij} = \left(LFMC_{ij} - Commuting_{ij}\right) * persons\_household_i \quad (14)$$

Where:

LFM_{ij}	= amount of labor migrants from region *i* to regions *j*, based on relative employment conditions
$LFMC_{ij}$	= direction of job occupation of labor force, based on relative employment conditions
$Commuting_{ij}$	= amount of commuters of region *i* to region *j*
$persons\_household_i$	= average amount of people per household in region *i*

As equation 14 assumes, only whole households migrate. The approach is therefore abstract, as in reality labor migrants do not have an average profile. Labor migration is, for instance, very dependent of household size as parents with many children will not migrate easily. Further, the average number of persons per household is assumed to have declined due to individualization during history. Eventually, the total number of labor out-migrants ($LFOUTM_i$) and labor in-migrants ($LFINM_j$) of each Dutch urban sector is defined in equation 15 respectively equation 16.

$$LFOUTM_i = \sum_j LFM_{ij} - LFM_{i=j} \quad (15)$$

$$LFINM_j = \sum_i LFM_{ij} - LFM_{i=j} \quad (16)$$

Where:

$LFOUTM_i$	= amount of labor out-migrants of region *i*, based on relative employment conditions;
$LFINM_j$	= amount of labor in-migrants of region *j*, based on relative employment conditions;
LFM_{ij}	= amount of labor migrants from region *i* to regions *j*, based on relative employment conditions
$LFM_{i=j}$	= amount of potential labor migrants who do not leave their region of origin *i*

Case results and strategy

The model's regional results are validated by regional statistics from 1972 until 1999. This relatively long period gives good opportunities for calibrating the model as good as possible. Especially central regions in The Netherlands are interesting in this respect, because the theoretical backgrounds of the approach applied are most strong here. The 'boundary-problem' as well as the 'problem of the limitless environment' are strongly reduced for central Dutch regions, as a central region's Dutch environment is modeled also, within a national closed system of internal flows.

For nationally central regions, for example *Utrecht* (Corop 17), good results were made. Results of different levels, such as population and houses, show an average estimation error of less than 3 percent. Underlying flows sometimes show results more diffused. This is mainly caused by the model structure of the gravity models used. Gravity models seem to have a rather robust character, as internal distances show to be quite dominant. Therefore, differences in size of Corop-regions result in unbalanced estimation errors. Overall results, however, are very acceptable.

Finally, the model developed is used in the field of transportation planning. The model's structure should be adequate to explore possible indirect spatial effects of large infrastructure measurements. In this respect, an interesting topical project is the realization of fast railway infrastructure (Transrapid) in the West of The Netherlands, as shown in Figure 20. The West of The Netherlands, also called 'Randstad', is defined by Corop-regions 17, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, and Corop 29 (Figure 10).

Figure 20 Planning of "Transrapid Randstad" in The Netherlands
(source: Consortium Transrapid Nederland)

The underlying idea of the “Transrapid Randstad” project is to accelerate socioeconomic developments in the Randstad, so that the Randstad will improve functioning as a metropolitan system. If so, the Randstad (about 6 million residents) could become more competitive with international areas as for instance London (about 7 million residents) and Paris (about 9 million residents). How does the model developed react on such a strategy?

The impact of the Transrapid project is simulated in the model by declining mutual decay powers b_{ij} in the gravity models used between Corop-regions involved. This simulates an increased internal accessibility of the Randstad regions, as supposed to be realized. Further, a simulation gives insight of Transrapid’s effects of migration and commuting, eventually resulting in indirect spatial effects. As Figure 21 shows, Transrapid investments lead to increasing internal flows of labor in the Randstad, illustrated by values of a performing index, which are greater than values of a reference performance index.

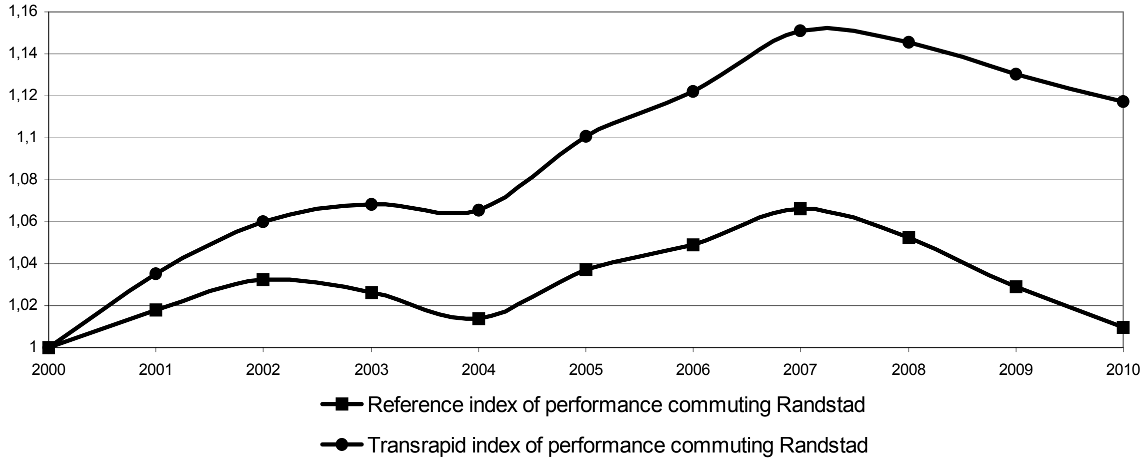

Figure 21 Effect of internal commuting in experiment *Transrapid Randstad*

Figure 21 illustrates a Randstad’s labor market widened by infrastructure measurements. Firms can recruit more easily by an increased labor force availability. This is an important pull factor of firms, which will be attracted by the Randstad. Further, economies of scale will result in more business activity, indicating an increased job availability. Increased employment conditions will attract migrants from outside the Randstad, by which not only more firms, but also more people will be concentrated in the Randstad. Eventually, the experiment confirms the realization of a large Dutch metropolis.

In the long term, however, diseconomies of scale limit urban growth. A particular threat, as indicated by the model results, is threatening decline of labor force in the long term. Declination of labor force threatens labor markets, partly caused by decreased commuting flows. Further, spread-effects of people and firms to outside the Randstad can possibly threaten the concentration of Randstad’s activities.

However, real indirect spatial effects of *Transrapid Randstad* are difficult to estimate. A more sophisticated approach would be to implement changed travel time distances in the gravity models more accurate. More accurate results would also demand more socioeconomic detail of processes. The model developed is, consequently, particularly of strategic value. More detail would enlarge tactical value, but would demand stronger software capacities.

Conclusions

The model developed illustrates a large urban network of 40 interconnected urban sectors. Hence, 'boundary-problems' in space and time, and the 'problem of the limitless environment' are strongly reduced, as region's Dutch environment is modeled also within a national closed system of internal flows. Regional model structures remain aggregated, however, as interregional flows are emphasized and software capacity limits the amount of entities applied. In this case, the model structure is mainly of strategic value in network analysis.

Setting up and designing the Dutch multiregional urban dynamics model was and is to a large extent a pedagogic methodological exercise. Implementing large disaggregated models in systems dynamics have proven to be an interesting challenge. This paper discussed an innovative approach of managing complexity in system dynamics, illustrated in the field of urban dynamics. The approach used, however, gives many opportunities for modeling disaggregated systems in general.

Discussion

The making of the case-project gave some insightful relationships of managing complexity in modeling large models in system dynamics, as portrayed in Figure 22.

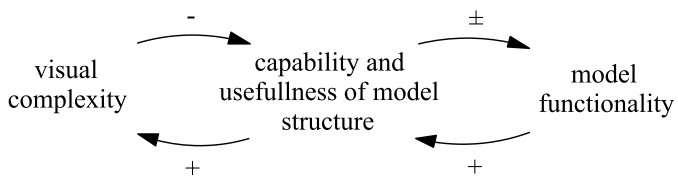

Figure 22 Aspects of managing complexity

Disaggregating processes enlarges a model's detail and (probably) its usefulness. In urban dynamics, for instance, multiple urban sectors can be showed (capability), not only approximating reality more accurate, but also generating more urban information and enlarging the model's usefulness with respect to policy analysis and decision-making. However, functionality refers also to the phenomenon that models can become too large in terms of entities allowed by software capacity and RAM (*Random Access Memory*) needed, as models will not operate at all. As STELLA® can possibly contain up to 32767 entities, kernel problems loom up if the modeler wants to exceed this maximum amount of entities allowed. On the other hand, an increased model functionality enables more opportunities in extending a model's capabilities and usefulness.

The left loop, as defined in Figure 22, illustrates relationships between visual complexity and model capabilities. This loop shows an increased model structure (increase of entities and relationships) will enlarge model's visual complexity. Declined surveyability makes it harder to comprehend model structure, so that model structures will have to remain simpler than possibly desired. Processes will have to be aggregated or eventually ignored, finally limiting the usefulness of system dynamics models.

As model structure limitation is defined by software and hardware capabilities, this is not a modeler's interest really. Enlarging model capabilities and its usefulness, however, definitely are. Hence, this paper suggests opportunities of enlarging model capabilities and its usefulness in system dynamics, as shown with the dotted graphic in Figure 23.

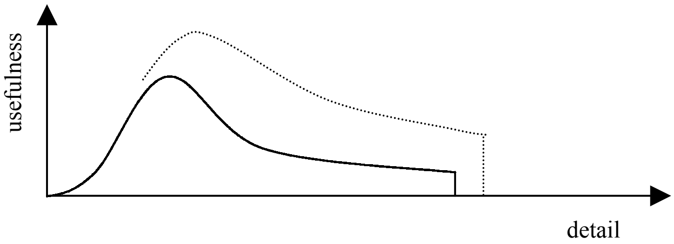

Figure 23 Idea of enlarged usefulness of system dynamics modeling

Although model structures simulate efficiently by arrayed structures, software limits model capabilities finally. However, limited detail can be overcome by new software technology. Moreover, just as in old DYNAMO-series, three-dimensioned arrays will increase model opportunities, as –if applied within the field of urban dynamics- migration or commuting can be segmented.

Although the double-array approach is applied to urban dynamics and transportation planning, the double-array approach's usefulness may spread many academic fields and its applications. The array-method applied enables matrix-based models (variables with two indices) and vector-based models (variables with one index) –often calculations that are made in software applications like Excel- to be implemented in system dynamics easily, while model structures remain manageable and visually understandable.

Urban planning, transportation planning, as well as economic and financial modeling for instance, can benefit from this approach in which all kinds of phenomena can be studied *dynamically*. All kinds of network models, either spatial or sectional interactions, can be studied with two-dimensional arrays. As traditional gravity models can be implemented in system dynamics, also (double) constrained gravity models, neural networks, logit-formulations, entropy maximizing models, input-output formulations, and shift-share models for instance, easily can be studied *dynamically* in system dynamics software environments.

As three-dimensional arrays would allow segmented spatial or sectional relationships to be studied, four-dimensional arrays would account for spatial as well as sectional analysis in system dynamics. Hence, new software technology will strengthen system dynamics' weaknesses. Together with its past strengths (easy-to-learn and easy-to-use approach to modeling), this will stimulate system dynamics in general as hard programming will become inconvenient more and more.

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