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Probabilistic modelling for simulating intra-urban residential migration

An application to the question of traffic noise annoyance

*Cécile Tannier*¹ (cecile.tannier@univ-fcomte.fr)

*Pierre Frankhauser*¹ (pierre.frankhauser@univ-fcomte.fr)

*Hélène Houot*¹ (helene.houot@univ-fcomte.fr)

*Gilles Vuidel*² (gvuidel@free.fr)

Corresponding author: *Cécile Tannier*

¹ ThéMA CNRS – Université de Franche-Comté
32, rue Mégevand
25 030 Besançon Cedex
France
Tel 1: +33 381 66 54 81
Tel 2: +33 381 66 54 29
Fax: +33 381 66 53 55

² Independent Computer Scientist
15C, rue de la Grette
25 000 Besançon
France
Tel 1: +33 381 83 22 68

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Abstract

This paper presents dynamic modelling of intra-urban residential migration of types of agents. The mathematical formalisation is described in detail. It is of a probabilistic nature and follows the time discrete approach of Markov chains. From an epistemological point of view, the proposed model is in keeping with recent research that aims to integrate economic and spatial modelling in the dynamics of urban systems.

A simulation model called *SimNoise* is presented as an application of the general modelling approach. The goal of the *SimNoise* model is to evaluate the impact of traffic noise on residential location dynamics. It allows the calculation of the probability that agents living in a given spatial unit will leave this location because of traffic noise. The basis for the construction of the model is a survey of traffic noise annoyance in the French city of Besançon. We demonstrate how the results of the survey can be used to operationalise and calibrate the *SimNoise* model.

Keywords: Urban dynamics, residential locations, traffic noise annoyance, probabilistic modelling, Markov chain

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Introduction

This paper aims to present in detail a probabilistic modelling concept, which allows the simulation of intra-urban residential migration. The general basis of the modelling concept has been previously presented (Tannier & Frankhauser, 2001), but the formalisation of individual migration probabilities, which was only outlined at the time, is now finalised.

The first part of this paper deals with the description of the mathematical formalisation which forms the base of the modelling concept. The methodological approach is situated in relation to various fundamental principles used in the modelling of spatial urban dynamics (Wilson, Allen & Sanglier, Weidlich & Haag...).

In the second part of the paper, the modelling concept is applied to the topic of traffic noise annoyance and its impact on intra-urban residential migration. Annoyance can be defined as “*a feeling of displeasure associated with any agent or condition believed to adversely affect an individual or a group*” (Berglund & Preis, 1997), and it is one of the two negative effects of traffic noise on the quality of life, with the second effect being the disturbance of sleep. From a methodological point of view, we discuss here the possibility of applying the modelling concept to a concrete case. The developed application is a simulation model called *SimNoise*. From a substantive point of view, the interest in the question of noise annoyance is twofold. Firstly, urban noise annoyance was much studied in the 1970s and at the beginning of the 1980s in a context of setting rules and laws for combating noise problems in industrialised countries. But since that time, the number of studies has strongly decreased. Secondly, few studies consider the degree of annoyance with respect to spatial and demographic factors which influence annoyance: the research presented here aims to do this. Finally, we discuss the possibility of testing and calibrating the *SimNoise* model with the results of a survey on noise annoyance realised in the city of Besançon¹.

1. The modelling concept: a probabilistic formalisation of intra-urban residential dynamics

The modelling concept proposed in this paper can be related mainly to two modelling approaches. On one hand, it is of a probabilistic nature, quite close to the original idea of Synergetic developed by H. Haken (1978). Thus, it is in keeping with some of the

¹ City of about 120,000 inhabitants in the East of France.

formalisations developed in physics, and subsequently used for modelling the dynamics of socio-economic systems. On the other hand, the modelling concept is close to the econometric formalisation of the hedonic location choice behaviour of individuals. This concept focuses on the behaviour of types of agents, where all the agents belonging to the same type are considered to have a homogeneous behaviour (see Diamond (1980) and Ellington (1981) for the first developments of hedonic modelling). Hence, we aim to situate the modelling concept with respect to the approaches closest to it or to which it refers more or less directly.

1.1 General context

Stemming from research in physics, the first spatial models of urban dynamics were introduced by A. G. Wilson (1981) and by P. Allen and M. Sanglier (1981), (Pumain *et al.*, 1989). Their models consider the phenomena on a macroscopic level. Types of individuals differentiated according to given socio-economic characteristics are introduced, with the differentiation of types of individuals being *a priori* and not resulting from a survey or observations. The approaches of Wilson and Allen and Sanglier concentrate on the dynamics of macroscopic configurations, that is the number of individuals of each type in each spatial unit. The dynamics of the modelled system are formalised through explicit relationships (mathematically defined as differential equations) linking the variables over the course of time. Thus, the dynamics are the result of the interactions between state variables (*e.g.* the flow of agents between each spatial unit or the attractiveness of each spatial unit). The functions linking the state variables are calibrated by considering the global behaviour of the modelled system to which they are related. It implies that the macroscopic behaviour of the system is defined *a priori* and does not emerge from the behaviour of the agents. Such modelling should be considered as a phenomenological approach, which does not directly transcribe individual choice behaviours.

The modelling developed by W. Weidlich and G. Haag (1988) also concentrates on the dynamics of macroscopic configurations. However, whereas the models of Wilson and Allen and Sanglier are deterministic, W. Weidlich and G. Haag introduce a probabilistic formalisation of the dynamics of the system by means of individual migration probabilities through individual transition rates, which describe the behaviour of the agents on the aggregated level. However, no specific assumptions are made about the way agents evaluate the attributes of spatial units. The calibration of the model takes into consideration macroscopic phenomena (*i.e.* the global behaviour of the system): the attractiveness of spatial units is calibrated with a migration matrix. In this sense, the modelling concept of Weidlich and Haag avoids the delicate problem of choice dynamics on the individual level. Dynamics

are introduced by means of a stochastic approach, the master equation, which is justified by the lack of information about behaviour on an individual level.

By proposing a general mathematical formulation and defining the concept of socio-dynamics, Weidlich and Haag emphasise the generality of their approach (Weidlich, 2000). However, some models derived from their research go further by introducing an explicit econometric formalisation (Haag & Frankhauser, 1989). Such a model is closer to our own modelling concept even if its approach remains macroscopic, which is not the case in the modelling approach presented here.

In epistemological terms, one of the most important differences between the social sciences and physics is that no basic principle exists which is comparable to Newton's relation between force, mass and acceleration. In physics, the fundamental goal of the models is to deal with change (change in the path of bodies or particles; change in the intensity of a field; change in the state of a system). State variables allow the description of macroscopic configurations, but some variables also characterise the behaviour of agents. In the social sciences, the applications of models stemming from physics usually avoid the introduction of individual behaviour. From this point of view, the case of Synergetic is exemplary considering its applications in physics and in the social sciences.

The starting point of Synergetic was a deep quantitative knowledge about the processes peculiar to the microscopic level of analysis. The fundamental goal was to understand how the emergence of a macroscopic system, showing a high degree of order, might be explained by microscopic behaviours. For example, the development of the laser theory was based on a deep knowledge concerning the dynamics of both the particles and the electromagnetic field as well as the interactions between the particles and the electromagnetic field. Certainly, in the social sciences, the interactions between agents are more complex than in the laser case. In particular, as D. Pumain (1997) has shown, socio-economic dynamics are driven by individual decisions, which refer to personal objectives. Weidlich and Haag did not explicitly take into account microscopic behaviours¹ because of the partial knowledge about individual location choices. Their choice was reinforced by the relatively poor calculation capacities of computers at that time and by the stability of the macroscopic scale. However, an increasing number of researchers in the social sciences share the idea that it is possible to acquire enough information about agent location behaviour to create models which allow the description of settlement dynamics on a macroscopic level (Sanders, 1999; Winder, 2000). Some socio-

¹Because the location behaviour of types of agents is explicitly taken into account in our modelling concept, it is closer to the original idea of Synergetic than to other geographical applications of it, especially those of Weidlich and Haag.

psychological modelling approaches also follow this direction (Vallée, 1995). All these approaches suppose a deep knowledge of the influences, the criteria and the processes involved in the choice behaviour of individuals. Finally, even if a basic theory of dynamics equivalent to that of physics does not exist in the social sciences, the increasing knowledge about individual behaviour obtained through observations and surveys in the field opens up new possibilities for a dynamic formalisation of the spatial behaviour of individuals.

Unlike geographical applications of modelling approaches stemming from physics, urban economics developed a great number of mathematical formalisations of individual choice behaviour based on the utility optimisation concept (Fujita, 1989). These formalisations aim to generate static equilibria or are used for studying the stability of the equilibria of dynamic systems. Furthermore, the multiple choice models introduce a probabilistic approach to the formalisation of individual choice behaviour, but they do not consider the dynamic of the modelled system. The results given by multiple choice models are conditional probabilities, within which formalisation is based on exponential functions including utility values in their exponent (Mac Fadden, 1997).

Here, it is particularly interesting to note that some recent research on the spatial dynamics of urban systems in economy and in geography has also tended to converge (Anas, Arnold & Small, 1997), as is the case for the modelling concept presented here.

1.2 Proposition of a probabilistic formalisation of intra-urban residential dynamics

The modelled phenomenon is the variation of the number of agents in each spatial unit, where a spatial unit can be a neighbourhood, a segment of a road...

The basic equation of the model allows the calculation of $p_j^{(g)}(t+\Delta t)$, which is the probability of having agents of type g in spatial unit j at time $(t+\Delta t)$.

$$p_j^{(g)}(t + \Delta t) = \sum_i p_{ij}^{(g)} \cdot p_i^{(g)}(t) \quad (1)$$

The calculation of the probability $p_j^{(g)}(t+\Delta t)$ is in keeping with Markovian logic which combines two individual probabilities:

- > $p_i^{(g)}(t)$ which is the probability of an agent of type g being in i at time t ,
- > $p_{ij}^{(g)}$ which is the probability of one agent of type g living in the spatial unit i going to one of the spatial units j ¹.

¹ To obtain the individual migration probability $p_{ij}^{(g)}$ we consider one departure spatial unit i and several arrival spatial units j . On the contrary, in the case $p_j^{(g)}(t+\Delta t)$, we consider one arrival spatial unit j and several departure spatial units i And in this case, each spatial unit is both an arrival and a departure spatial unit.

The formalisation of the migration process is based on the use of conditional probabilities, which link the state of the system at a time t to its state at a time $t + \Delta t$.

The probability $p_{ij}^{(g)}$ is obtained through the combination of two multiplicative terms: the choice factor $\varphi_{ij}^{(g)}$ and the propensity to move $\omega_i^{(g)}$ (figure 1).

$$p_{ij}^{(g)} = \varphi_{ij}^{(g)} \cdot \omega_i^{(g)} \quad (2)$$

The propensity to move $\omega_i^{(g)}$ is a mobility term. It indicates the proportion of the agents who would leave spatial unit i to go to spatial unit j . In that sense, it represents the event probability. The choice factor $\varphi_{ij}^{(g)}$ can be interpreted as a weighting of this event probability.

It is interesting to note that, because the propensity to move is an event probability, the sum of the individual migration probabilities $p_{ij}^{(g)}$ is equal to $\omega_i^{(g)}$.

$$\omega_i^{(g)} = \sum_{j \neq i} p_{ij}^{(g)} \quad (3)$$

Then, by the requirement of normalisation, we must have:

$$\sum_{j \neq i} p_{ij}^{(g)} + p_{ii}^{(g)} = 1 \quad (4)$$

Thus,

$$p_{ii}^{(g)} = 1 - \omega_i^{(g)} \quad (5)$$

The choice factor $\varphi_{ij}^{(g)}$

The term $\varphi_{ij}^{(g)}$ represents the relative attractiveness of a spatial unit j ($Y_{ij}^{(g)}$) with respect to all the attractiveness measures of all the spatial units j , for an agent of type g living in the spatial unit i ¹.

$$\varphi_{ij}^{(g)} = \frac{Y_{ij}^{(g)}}{\sum_{j \neq i} Y_{ij}^{(g)}} \quad \text{with} \quad Y_{ij}^{(g)} = \sqrt{D_{ij}^{(g)} \cdot F_j} \quad (6)$$

The attractiveness $Y_{ij}^{(g)}$ results from the combination of a dissatisfaction level $D_{ij}^{(g)}$ with the evaluation of the land supply F_j ².

¹ Here we consider that it is impossible for the attractiveness measures of all the spatial units to be simultaneously equal to 0.

² Concerning the justification of the choice of the geometrical mean as aggregation operator, see (Tannier & Frankhauser, 2001).

Figure 1: Attributes, variables and parameters

Attributes and variables	
Elementary spatial units (segments of road)	
$i = 1, 2, \dots, k$	departure spatial units
$j = 1, 2, \dots, k$	arrival spatial units
Types of agents	
$\mathbf{g} = (g_1, g_2, \dots, g_z)$	
$\mathbf{a}^{(g)}(i) = (a_1, a_2, \dots, a_p)$	For an agent of type g , evaluation of the attributes $(1, 2, \dots, p)$ characterising a spatial unit i
$\mathbf{s}^{(g)}(j) = (s_1, s_2, \dots, s_n)$	For an agent of type g , evaluation of the attributes $(1, 2, \dots, n)$ characterising a spatial unit j
$A_i^{(g)} \equiv A_i$	For an agent of type g , synthetic evaluation of a spatial unit i
$S_j^{(g)} \equiv S_j$	For an agent of type g , synthetic evaluation of a spatial unit j different from i
R_j	Number of available settlement sites in a spatial unit j
$D_{ij}^{(g)}$	Dissatisfaction level between i and j for an agent of type g
$F_{j \neq i}$	Evaluation of the land supply in a spatial unit $j \neq i$
$Y_{ij}^{(g)}$	Attractiveness of the spatial unit $j \neq i$ for an agent of type g living in the spatial unit i
M_{ij}	Global interest to move
$\xi_{(A_i)}^{(g)}$	Individual mobility of an agent of type g living in the spatial unit i
$\omega^{(g)}$	Individual propensity to move of an agent of type g living in the spatial unit i
$\Phi_{ij}^{(g)}$	Choice factor of an agent of type g living in the spatial unit i
Parameters	
δ and ν	Parameters of the logistic function for the land supply $F_{j \neq i}$
β^g and μ^g	Parameters of the logistic function for individual mobility $\xi_{(A_i)}^{(g)}$
γ and α	Parameters of the logistic function for the global interest to move M_{ij}
m	Parameters used for taking into account the signification of the synthetic evaluations A_i and S_j (satisfaction or non satisfaction)

The introduction of the evaluation of land supply F_j is justified as following: if an agent feels an impulse to leave his/her spatial unit i , he/she will look at the state of the residential offer in the other spatial units j . Then, if the evaluation of the land supply in a given spatial unit is good, the agent may seriously look for housing in this spatial unit. The evaluation of the land supply of the agents is represented using a logistic function because it allows the modelling of saturation phenomena, such as observed in the case of land supply (*formula 7*). The function F_j is defined for all the agents whatever their type, which means that the evaluation of land supply does not vary according to the type of the agents.

$$F_{j \neq i} = \frac{1}{e^{-\delta(R_j - v)} + 1} \quad \text{where } R_j \text{ is the number of available settlement sites in a spatial unit } j \quad (7)$$

The Dissatisfaction Level $D_{ij}^{(g)}$ represents the divergence between the actual situation of an agent (his/her life in the spatial unit i) and one other possible situation (a spatial unit j different from i). The Dissatisfaction Level is a push-pull indicator: the higher it is, the more an agent feels an impulse to leave his/her spatial unit i . The calculation of the Dissatisfaction Level is based on two evaluation terms:

- A_i which is a measure of the evaluation of the actual residential zone of the agent,
- S_j which is a measure of the evaluation of a potential residential zone j .

$$D_{ij}^{(g)} = \text{MAX}[m(A_i - S_j), 0] \quad (8)$$

When applying the modelling concept, A_i and S_j represent either the evaluation of the *satisfaction* of an agent or the evaluation of the *non satisfaction*. Hence, the necessity to introduce the parameter m : if A_i and S_j are *satisfaction indicators*, then the parameter m takes the value (-1). Conversely, if A_i and S_j are *non satisfaction indicators* (e.g. noise annoyance), then the parameter m takes the value (1).

A_i and S_j are synthetic evaluations of the attributes of each spatial unit by each type of agent. Actually, each spatial unit i is characterised by a vector of attributes $\mathbf{a} = (a_1, a_2, \dots, a_p)$ whereas each spatial unit j is characterised by a vector of attributes $\mathbf{s} = (s_1, s_2, \dots, s_n)$. In fact, most of the attributes belong to both vectors \mathbf{a} and \mathbf{s} but a difference is introduced between vectors \mathbf{a} and \mathbf{s} to point out a slightly different semantic interpretation of the attributes in the two cases. Indeed, when an agent evaluates a spatial unit j , the attributes are in some sense location criteria (expected attractiveness, assumed satisfaction etc.). But, when an agent evaluates his/her own spatial unit i , he/she is influenced by his/her everyday experience. In this case, the attributes are satisfaction criteria rather than location criteria. Thus, the distinction between the two vectors of attributes corresponds to the existence of two different evaluation logics.

Each type of agent evaluates each attribute of each spatial unit. The evaluation of the attributes is formalised through mathematical functions, which relate the value of an attribute (x) to the evaluation of this attribute by a given type of agent $\mu(x)^{(g)}$ ¹. The synthetic evaluations A_i and S_j result from the aggregation of the values of evaluation of the corresponding attributes (vectors \mathbf{a} and \mathbf{s}).

¹ Such an evaluation may usefully be formalised using the fuzzy sets theory.

The propensity to move $\omega_i^{(g)}$

The propensity to move $\omega_i^{(g)}$ is a function of two terms: individual mobility $\xi(A_i)^{(g)}$ and the global interest to move M_{ij} .

$$\omega_i^{(g)} = f [\xi(A_i)^{(g)}; M_{ij}] \quad (9)$$

The function f should be defined when applying the modelling concept, with respect to the field of application.¹ For the first term $\xi(A_i)^{(g)}$ we chose a logistic function which reads:

$$\xi(A_i)^{(g)} = \frac{1}{e^{-\beta^g(A_i - \mu^g)} + 1} \quad (10)$$

The basis for the formalisation of $\xi(A_i)^{(g)}$ is the assumption that individual mobility is a function of the evaluation of the actual situation of the agent A_i . The variation of the mobility according to the type of agent is modelled through the parameters β^g and μ^g of the function. Each function $\xi(A_i)^{(g)}$ (*i.e.* each couple of values β^g and μ^g) corresponds to a particular behaviour.

The parameter β^g controls the spreading of the curve whereas the parameter μ^g determines the position of the value $\xi(A_i)^{(g)}$ which equals 0.5 with respect to the initial value A_i . The lower the value of μ^g , the sooner the value of $\xi(A_i)^{(g)}$ increases. The lower the value of β^g , the smaller the range of the results: β^g determines in which range an agent is switching; it is used for modelling the fact that the behaviour of an agent is more or less categorical and clear-cut. Concerning the global interest in moving M_{ij} , an urban area offers great opportunities to move if on one hand, the attractiveness of the spatial units is clearly distinct, and on the other hand the land market makes moving easy. This observation provides the basis for the assumption that the global opportunity to move in an urban area varies according to the effective attractiveness measures of the different spatial units. Hence, the requirements for this function M_{ij} are as follows:

- M_{ij} has to be a monotone increasing function,
- the results should belong to the interval [0;1],
- M_{ij} should slowly begin to increase and then, slowly saturate.

Actually, a logistic function was again chosen.

¹For the choice of an appropriate operator, see (Tannier & Frankhauser, 2001).

$$M_{ij} = \frac{1}{e^{-\gamma \left[\frac{\sum_{j=1}^n Y_{ij}^{(g)}}{n} - \alpha \right]} + 1} \quad (11)$$

The function M_{ij} is defined for all types of agents, which means that the parameters α and γ do not depend on the type of agents. However, when applying the model, the results given by the function M_{ij} vary according to the types of agents because the values of $Y_{ij}^{(g)}$ are different with respect to the considered agent type.

It should be noted here that the function $\xi(A_i)^{(g)} = f[\beta^{(g)}, \mu^{(g)}, A_i^{(g)}]$ depends explicitly on the type of agents (g), whereas the function $M_{ij} = f[\alpha, \gamma, Y_{ij}^{(g)}]$ depends only implicitly on the types of agents through the mean evaluation of attractiveness measures.

Some general comments on the modelling concept

A preliminary remark concerns the definition of the considered analysis levels. Three analysis levels have to be defined.

- 1) The *individual level* allows the consideration of each individual; it is a base for the statistical extraction of types of agents according to their behaviour.
- 2) The *agent type level* allows the consideration of types of agents of homogeneous behaviour¹. The definition of types of agents is based on the ergodic assumption which assumes that the evaluation of the different characteristics of places by an agent may fluctuate according to his/her state of mind, but these fluctuations do not exceed the variations in the global evaluation for that type of agent. In other words, it is assumed that the mean behaviour of an agent over a given time interval is equivalent to the mean behaviour of several agents belonging to the same type.
- 3) The *aggregated level* allows the consideration of all the agents living in a given spatial unit, whatever their type.

At the heart of the modelling concept, a fundamental assumption is that individual migration decisions are taken independently: no reference to agents other than g are considered, and no spatial units other than the neighbourhoods i and j appear in the formula. However, it does not mean that the evaluation or the mobility of an agent is not influenced by the behaviour of other agents: we only assume that this influence acts in a global way on each agent. Indeed, the attractiveness measures include the interactions between agents in the sense that the evaluation of each agent is influenced by the presence of other agents of different types through the vectors of attributes of the spatial units. From an epistemological point of view, such reasoning is very close to the notion used in physics of "mean field", which assumes that

¹ Hence, when talking about a microscopic level, it may refer to either a purely individual level or an agent type level.

all influences exerted by all the particles on an individual particle may be approximated by one global influence function.

Formula 12 corresponds to the developed form of formula 2. It allows a better understanding of some other aspects of the modelling concept.

$$p_{ij}^g = \frac{\sqrt{D_{ij}^{(g)} \cdot F_{j \neq i}}}{\sum_j \sqrt{D_{ij}^{(g)} \cdot F_{j \neq i}}} \cdot f \left[\left(\frac{1}{e^{-\beta(A_i - \mu)} + 1} \right); \left(\frac{1}{e^{-\alpha \left[\frac{1}{n} \left(\sum_j (\sqrt{D_{ij}^{(g)} \cdot F_{j \neq i}}) \right)^{-\gamma} \right]} + 1} \right) \right] \quad (12)$$

Firstly, as commonly accepted in the literature, we consider a migration process to consist of two phases: the evaluation phase, which consists of the search for a convenient site, and the phase of the choice of a site. Following the evaluation phase, an agent can still choose all the residential zones, even if some of them are more attractive than others. The very decision to move to a specific location is taken during the choice phase. The adopted formalisation allows the preservation of the complexity of the migration process: evaluation and choice are distinguished because they are of a different nature, but in the application/implementation of the model, these two phases are considered as being interactive and not simply successive.

Secondly, the fact that a product links the choice factor $\varphi_{ij}^{(g)}$ and the propensity to move $\omega_i^{(g)}$ refers to the assumption that the evaluation of the spatial units is independent of the intrinsic mobility of the agents. Considering a given type of agent living in a given zone i , the variation of the probability $p_{ij}^{(g)}$ is determined by the ratio between the attractiveness value of one spatial unit j and the attractiveness of all the other spatial units j . The maximum value of the ratio is 1. If it is attained (all the attractiveness values are equal to 0 except the attractiveness of a considered spatial unit j), the probability $p_{ij}^{(g)}$ is equal to the propensity to move $\omega_i^{(g)}$.

We will conclude this section with two final comments concerning the dynamic aspects of this approach to modelling.

- 1) The decision to rent or to buy housing is a time discrete process, for which it is not possible to know the exact time of occurrence. Such an observation explains the choice of a time discrete modelling approach: the spatial dynamics of the modelled system is driven by the sequence of individual decisions and the individual probability of moving is not expected to change in a time-continuous way.
- 2) We approach the sequence of decisions of each agent over the course of time from the point of view of the Markov assumption: agents belonging to type g and considering a migration from i to j will always decide in the same way. Thus, we assume that the individual history of agents, in fact, their previous experience, does not influence their evaluation of the attractiveness of the neighbourhood and

their mobility. We may justify this assumption since, firstly, the types of agents are defined according to the migration behaviour of the agents, and secondly, the conditional probability of moving for a given agent depends on his/her type (g).

2. The simulation model *SimNoise*: basic hypothesis and structure

In the *SimNoise* model, the elementary spatial units are segments of roads, which are subject either to traffic noise only or to no noise. Actually, because of the focus of the research (*i.e.* the impact of traffic noise), the model takes into account only sets of residential buildings directly exposed to traffic flow and does not consider all the residential zones of an urban area.

The goal of the model is to evaluate the impact of traffic noise on residential location dynamics. It allows the calculation of the probability that the agents living in a given spatial unit will leave this location because of the traffic noise. Such a goal implies that the *SimNoise* model considers each spatial unit with respect to the whole urban area. In this respect, it differs from the general modelling concept which concentrates on the migration flow between all residential zones of an urban area, and thus focuses on the competition between the different zones.

The basis for the construction of the *SimNoise* model is a survey on traffic noise annoyance in the French city of Besançon. The survey was carried out in 1999 by H. Houot for the Urban District of Besançon (Houot, 1999)¹. 7,454 postal questionnaires were sent out and 2,702 persons responded. The size of the sample retained for the research presented here is about 2,000 individuals. The reduction in the size of the sample is explained by the deletion of individuals exposed to noise of an overly specific type and of individuals from categories in which the sample size was too small to be statistically representative.

The analysis of the results of the survey confirmed an initial hypothesis: that traffic noise annoyance varies according to five spatial variables characterising the segments of a road. The five variables are as follows: noise exposure level; the type of the road, which determines the nature of the traffic flow (*e.g.* bus traffic of more than 500 vehicles per a day generates a higher annoyance than composite traffic); the daily rate of traffic flow; the quality of building soundproofing; and the type of the surrounding built-up pattern (individual or collective housing, high or low built-up density, homogeneous or heterogeneous types of buildings...).

¹ Before this survey was undertaken in 1999, a previous one on the same theme had already been done in 1994. The 1994 survey was effectively a pilot for the 1999 survey: this along with other complementary studies allowed the definition of the basic hypothesis for the 1999 survey.

The basic hypothesis and the structure of the *SimNoise* model were defined after an integration of, on one hand, the survey and the actual knowledge of the subject of noise and, on the other hand, the general modelling concept presented in the first part of the paper. From a methodological point of view, we verified that the assumptions governing the modelling concept correspond to the known behaviour of agents with respect to traffic noise annoyance. In particular, the same analysis level is considered both in the general modelling concept and in the specific area of traffic noise annoyance. It is interesting to note that analysing noise annoyance while considering the agent type level represents an intermediary level between the aggregated analysis of local authorities and the individual analysis level of social-psychologists. Such an intermediary level is particularly well suited to tackle the question of annoyance by focusing on the interactions between spatial and socio-demographic factors.

Concerning the thematic assumptions of the model, it was decided to retain only the first order variable describing the noise environment of a road segment, which is the noise exposure level. The second assumption is the variation of the annoyance expressed for a given noise exposure level according to individual variables. Statistical calculations on the survey data (Chi² independence test and calculation of contingency coefficient) allowed the identification of significant individual variables. Three supplementary assumptions ensued from the analysis.

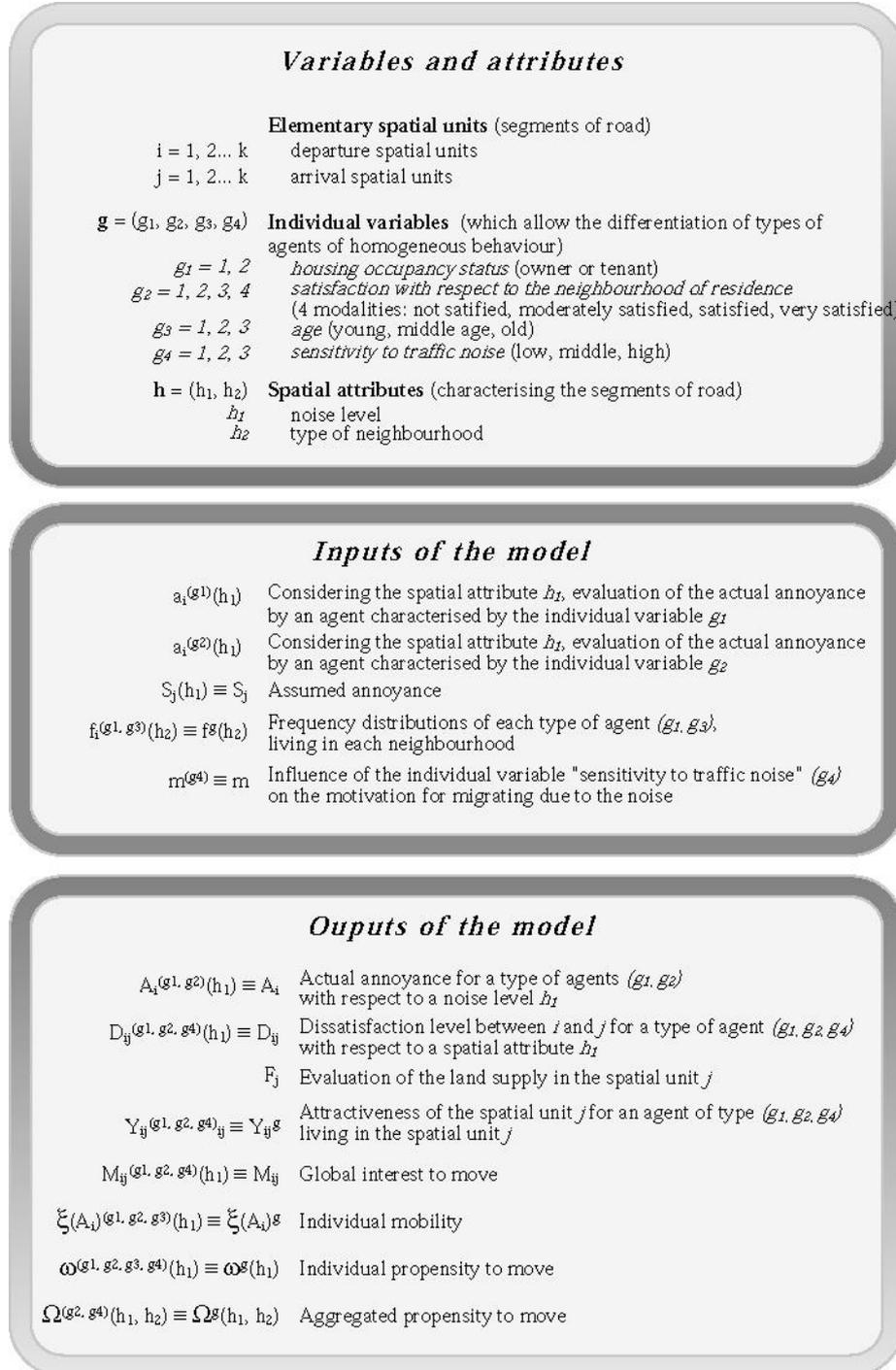
- 1) No relation exists between noise annoyance and the socio-economic profile of the agents.
- 2) For a given noise exposure level, the noise annoyance varies with respect to two individual variables: the housing occupancy status (owner or tenant)¹ and the satisfaction with respect to the neighbourhood of residence. These two individual variables amplify or compensate for the effects of noise on the expressed annoyance of individuals.
- 3) For a given noise exposure level, individual mobility due to noise varies with respect to three individual variables: the housing occupancy status, the age and the level of sensitivity to traffic noise (partly resulting from the previous noise experience of the agents).

Finally, for a given noise exposure level, the annoyance and its effect on the mobility of the agents vary with respect to four individual characteristics: housing occupancy status, satisfaction with respect to the neighbourhood of residence, age and level of sensitivity to traffic noise (*figure 2*). These four variables are considered as being independent. Existing dependencies are taken into account in the course of modelling by mean of mathematical

¹ In reality, the influence of this variable occurs only at low noise levels, but we do not take into account the existence of such a threshold in the model.

relationships. The distinction of individual variables allows the differentiation of types of agents of homogeneous behaviour, with each type of agent being a unique combination of the modalities of the variables.

Figure 2: Inputs and outputs of the SimNoise model



Having laid down the basis of the *SimNoise* model, the next step is the concrete introduction of the different variables in the model. As explained in the first part of the paper, the modelling is based on evaluation rules, defined as mathematical functions which relate the value of an attribute (x) to an evaluation value $\mu(x)^g$. In the case of the *SimNoise* application,

the evaluations of the attributes of the spatial units are not formalised through mathematical functions. The evaluation rules are expressed by tables extracted directly from the survey. Three tables were created:

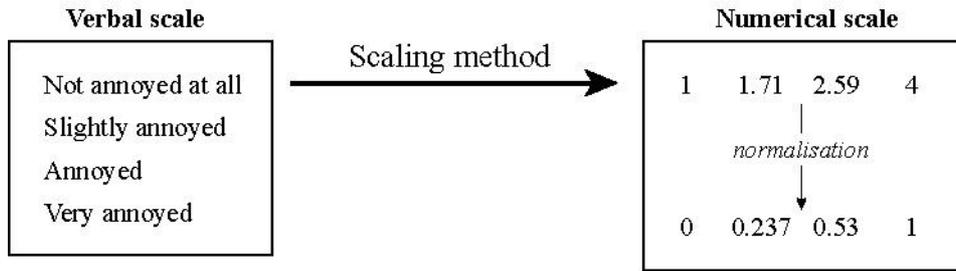
- $a_i^{(g_1)}(h_1)$: values of annoyance for each noise level (h_1) and each modality of the variable (g_1) “Status as Housing Occupant”
- $a_i^{(g_2)}(h_1)$: values of annoyance for each noise level (h_1) and each modality of the variable (g_2) “Neighbourhood Satisfaction”
- $S_j(h_1)$: mean values of annoyance for each noise level (community annoyance¹).

The creation of these three tables required the transformation of the survey data. In the survey, noise annoyance as perceived by the individuals was expressed on a verbal 4 point scale. By using a statistical scaling method, it was possible to transform this information into numerical values representing the annoyance of the agents (*figure 3*). Such a transformation is in keeping with the theory of Psychophysics, the basis of which was defined by Fechner (1860). We chose “*Optimal Invariant Encoding*” as a scaling method which considers the assumption that the modalities (ranks) R_z of an ordinal scale of annoyance can be associated to numerical values on a scale of intervals (Thurstone, 1927; Saffir, 1937). The initial data is a table of conditional frequencies of annoyance values with respect to noise exposure levels (f_{a/h_1}). On the basis of this table, the determination of the scale of intervals is obtained through the maximisation of the part of the variance between the stimuli (*i.e.* noise exposure level) in the total variance. A statistical multivariate analysis (*i.e.* factorial analysis²) can be used to resolve such a problem of maximisation (Maurin, 1984). The procedure is defined as follows: the factorial analysis is applied to the table (f_{a/h_1}). The extreme values of the scale of intervals are fixed at X_1 equal to 1 and X_q equal to the number of values of the initial ordinal scale (in this case, q is equal to 4). The interval between each point of the scale of intervals that is researched is proportional to the coordinates of each modality (ranks) R_z of the ordinal scale of annoyance on the first factor of the factorial analysis. The normalisation of the values of the scale of intervals means that the figures obtained lie between 0 and 1.

¹ This aspect is developed and discussed in (Houot, 1999).

²In French, « *analyse factorielle des correspondances* ».

Figure 3: Transformation of the ordinal scale of annoyance into a scale of intervals



In addition to the spatial attribute “noise exposure level” (h_1), figure 2 shows the existence of another spatial attribute (h_2), which is the “type of neighbourhood”. A frequency distribution of the types of agents living in this type of neighbourhood $f^{(g^1, g^3)}(h_2)$ corresponds to each type of neighbourhood. Such data are directly extracted from the survey¹.

On the basis of the four tables of input data ($a_i^{(g^1)}(h_1)$; $a_i^{(g^2)}(h_1)$; $S_j(h_1)$; $f^{(g^1, g^3)}(h_2)$), a simulation with the *SimNoise* model leads to seven tables of results.

The first result is the actual annoyance (A_i) for an agent of type (g_1, g_2) living in the spatial unit i . The calculation of the actual annoyance (A_i) consists of the aggregation of two values of evaluation: $a_i^{(g^1)}(h_1)$ (value of annoyance according to the housing occupancy status and the noise exposure level) and $a_i^{(g^2)}(h_1)$ (value of annoyance according to neighbourhood satisfaction and the noise exposure level). Since we know that the evaluation of the noise annoyance by the agents results from a compensation between the two individual determinants of the annoyance (neighbourhood satisfaction and housing occupancy status), it must involve the choice of an aggregation operator having this property.

$$A_i = \otimes [a_i^{(g^1)}(h_1), a_i^{(g^2)}(h_1)] \quad (13)$$

... where \otimes is an aggregation operator, which has to be defined through the calibration of the *SimNoise* model (see part 3 of this paper).

The second result given by *SimNoise* is the assumed annoyance when considering the spatial unit j different from i . The assumed annoyance is simply and directly the mean value of noise annoyance for each noise level ($S_j \equiv S_j(h_1)$).

The Dissatisfaction Level D_{ij} is the third result obtained with *SimNoise*. It is defined as a function of the difference between the actual annoyance and the assumed annoyance.

$$D_{ij} = \text{MAX} (m^{(g^4)} (A_i - S_j), 0) \quad (14)$$

¹The sample of data does not allow the calculation of statistically representative values of $f^{(g)}(h_2)$ when taking into account the four individual variables (g_1, g_2, g_3, g_4). Indeed, with a sample of about 2,000 individuals and considering 64 types of agents, it would be possible to have a minimum of 30 individuals of each type in the sample. However, this is not the case for the considered sample of data in which some types of agents are under represented. Further explanations and justifications about the choice of the individual variables (g_1, g_3) will be given in the third part of this paper, which presents a first application of the *SimNoise* model.

Hence, two differences between *SimNoise* and the general modelling concept have to be emphasised. Firstly, the actual annoyance A_i considers one type of agent (agent type analysis level) whereas the assumed annoyance S_j is an aggregated value considering all the types of agents. Secondly, apart from the fact that the parameter $m^{(g^4)}$ considers A_i and S_j as non satisfaction indicators, it also represents the effect of the agents' sensitivity to traffic noise, which influences the agents' motivation for migrating due to noise and influences the agents' evaluation of the zones j .

The analysis of the survey data leads to identify three levels of noise sensitivity (low, medium and high) on the basis of the actual situation of the agent (does he/she want to move because of the noise) and on the basis of his/her previous noise experience (did he/she move previously because of noise). The analysis of the data also shows that, whatever the noise level, the evaluation of the assumed annoyance is always over-estimated by the highly sensitive agents and under-estimated by the less sensitive agents. From this observation we can assume that the dissatisfaction level D_{ij} is over-estimated or under-estimated by the agents with respect to their noise sensitivity.

- In the case of highly noise sensitive agents, $m^{(g^4)} > 1$ and $D_{ij} > (A_i - S_j)$
- In the case of agents of medium sensitivity, $m^{(g^4)} = 1$ and $D_{ij} = (A_i - S_j)$
- In the case of agents who are not sensitive, $0 < m^{(g^4)} < 1$ and $D_{ij} < (A_i - S_j)$

The choice of a linear function for calculating D_i is also justified by the fact that the over-estimation or under-estimation of D_{ij} is particularly strong when the value of the difference $(A_i - S_j)$ is high.

Referring to the general modelling concept, the dissatisfaction level is one of the two terms which allows the calculation of the attractiveness Y_{ij}^g .

$$Y_{ij} = (D_{ij} \cdot F_j)^{\frac{1}{2}} \quad (15)$$

The focus point of the *SimNoise* model is the number of agents that would leave a given spatial unit, which differs from the general modelling concept. For that reason, we chose to consider the evaluation of the land supply F_j as a constant value equal to 1: the number of available settlement sites in each noise level does not play any role in the evaluation of the attractiveness of each noise level. In the general modelling concept, the attractiveness values are obtained by the aggregation of the two terms D_{ij} and F_j (formula 15). Because one of these two terms F_j in the *SimNoise* model is a constant equal to 1, it is possible to eliminate the term F_j in formula 15, which also leads to the elimination of the aggregation operator. Thus, in the *SimNoise* model, the calculation of the attractiveness Y_{ij} is given by formula 16.

$$Y_{ij} = (D_{ij})_i^{-1} = D_{ij} \quad (16)$$

Finally, the formalisation of the evaluation phase is based on four evaluation indicators (A_i , S_j , m , D_{ij}), which deal with various phenomena of a different nature. Such a formalisation allows the modelling of some rather complex aspects of the decision process. In particular, the parameter $m^{(g)}$, which represents the influence of the agents' motivation on their evaluation, introduces an aspect of the final choice from the evaluation phase.

Henceforth, we enter the formalisation of the migration phase with the calculation of the fourth result of the model, that is the individual propensity to move $\omega_i^g(h_i)$. Regarding the general modelling concept, $\omega_i^g(h_i)$ is a mobility term which represents the probability that the agents of type g will leave the noise level of the spatial unit i to go to one of the other spatial units j characterised by a different (lower) noise level. Two terms determine the mobility of an agent: individual mobility $\xi(A_i)^g$ and the global interest to move M_{ij} . Their aggregation determines the propensity of a type of agent to move.

$$\omega_i^g(h_i) = \frac{\xi(A_i)^g + M_{ij}}{2} \quad (17)$$

No information is given by the survey about the relationship between individual mobility $\xi(A_i)^g$ and the global interest to move M_{ij} . The lack of actual knowledge on this topic explains the choice of a very simple aggregation operator (the arithmetical mean), which fits the assumption that M_{ij} and $\xi(A_i)^g$ are two independent contributions to the propensity to move $\omega_i^g(h_i)$. Indeed, the calculation of the propensity to move includes no direct interaction between M_{ij} and $\xi(A_i)^g$.

The individual mobility of the types of agents $\xi(A_i)^g$ depends on their actual annoyance.

$$\xi(A_i)^g = \frac{1}{e^{-\beta^g(A_i - \mu^g)} + 1} \quad (10)$$

The form of the function varies according to two individual variables: age and housing occupancy status. Their influence is represented by the parameters β^g and μ^g of the logistic function. Thus, a given couple of parameters β^g and μ^g corresponds to a given type of agent. The calculation of the term $\xi(A_i)^g$ is based on a differentiated socio-demographic reaction toward traffic noise which leads to a differentiated mobility.

The second term of the Individual Propensity to Move (*i.e.* the Global Interest to Move M_{ij}) is a global measure of all the dissatisfaction levels. Actually, whatever the individual mobility of

an agent, his/her propensity to move is even higher when the difference between his/her actual situation and all the other assumed situations is high. M_{ij} is defined as a mean function of all the dissatisfaction levels with the parameters α and λ not being dependent on the type of the

$$M_{ij} = \frac{1}{e^{-\gamma \left[\frac{\sum_{j=1}^n D_{ij}}{n} - \alpha \right]} + 1} \quad (18)$$

agents.

Here we tackle the last aspect of the *SimNoise* model, the calculation of the Aggregated Propensity to Move Ω_i . The Aggregated Propensity to Move represents the probability that the agents living in the same spatial unit will leave it whatever their type.

The formalisation of the Aggregated Propensity to Move is based on the formula of composed probabilities: $P(A \cap B) = P(B | A) \cdot P(A)$

... where the event (A) is “agent of type g ”

... and the event (B) is “leaving the spatial unit i ”

... and the event (B | A) is “leaving the spatial unit i for an agent on the condition that he/she is of type g ”

... and the event (A \cap B) is “being of type g and leaving the spatial unit i ”.

Considering the *SimNoise* model, $P(A)$ corresponds to the term $f^g(h_2)$ and $P(B | A)$ corresponds to the term $\omega_i^g(h_1)$.

We previously saw that the model considers agents living in spatial units, with each spatial unit belonging to both a noise level (h_1) and a type of neighbourhood (h_2). This last element “type of neighbourhood” occurs only at this step of the model. Hence, the Aggregated Propensity to Move of a given spatial unit i (noise level h_1 and type of neighbourhood h_2) is obtained by combining the individual propensity to move $\omega_i^g(h_1)$ with the frequencies of types of agents $f^g(h_2)$:

$$\Omega_i(h_1, h_2) = \sum_{g=1}^z \omega_i^g(h_1) \cdot f_g(h_2) \quad (19)$$

We would like to emphasise here a specific aspect of the model: we previously explained that the agents are differentiated by various individual characteristics which are supposed to be statistically independent. Such an assumption may seem very restrictive (in fact, too far removed from the observed reality), but it appears consistent with the modelling approach which considers the compensation phenomena between the variables at the time of the aggregation of the different indicators. The assumption of the independence of the variables allows the extraction of behavioural rules from the data survey without confronting samples

of individuals that are too small. Indeed, the evaluation or migration rules are obtained on the basis of statistical calculation using the whole population sample and not by using sub-sets of individuals: at each step of the modelling process, ad hoc sub-sets of individuals are defined from the whole population sample. This allows the definition of statistically representative rules.

Finally, a last point should be emphasised concerning the results of the model themselves: whereas the actual annoyance and the individual propensity to move come under the agent type analysis level, community annoyance and the aggregated propensity to move come under the aggregated analysis level.

3. *SimNoise* application and simulation results

The *SimNoise* model considers eight noise exposure levels¹ and seven types of neighbourhoods² which characterise the segments of a road.

Two aspects are included in testing the model, each of them corresponding to a specific series of simulations. The first aspect is the calibration of the model (the choice of the values of the parameters and the choice of the aggregation operators). The second aspect is the test of the sensitivity of the model to variations of input data, whose goal is the evaluation of the consistency of the simulation results with respect to the knowledge on the topic of noise annoyance.

3.1 Using the survey data for calibrating the model

Different methods have been applied to determine the values of the parameters and to choose the aggregation operators. They are presented from the less empirical to the more empirical.

Choice of a suitable aggregation operator for calculating the actual annoyance A_i

$$A_i = \otimes [a_i^{(g1)}(h_i), a_i^{(g2)}(h_i)] \quad (13) \dots \text{where } \otimes \text{ is the aggregation operator}$$

On the basis of the survey data, the three values $a_i^{(g1)}(h_i)$, $a_i^{(g2)}(h_i)$ and A_i can be calculated. The comparison of the values of actual annoyance A_i obtained by using different aggregation operators with the values given by the survey shows the generally high quality of the results when using the geometrical mean. Thus, the actual annoyance is now calculated as following:

$$A_i = [a_i^{(g1)}(h_i), a_i^{(g2)}(h_i)]^{1/2}$$

¹Noise level 1: 50,5 to 55,5 dBa

Noise level 2: 55,5 to 60,5 dBa

Noise level 3: 60,5 to 63,5 dBa

Noise level 4: 63,5 to 66,5 dBa

Noise level 5: 66,5 to 69,5 dBa

Noise level 6: 69,5 to 72,5 dBa

Noise level 7: 72,5 to 75,5 dBa

Noise level 8: 75,5 to 78,5 dBa

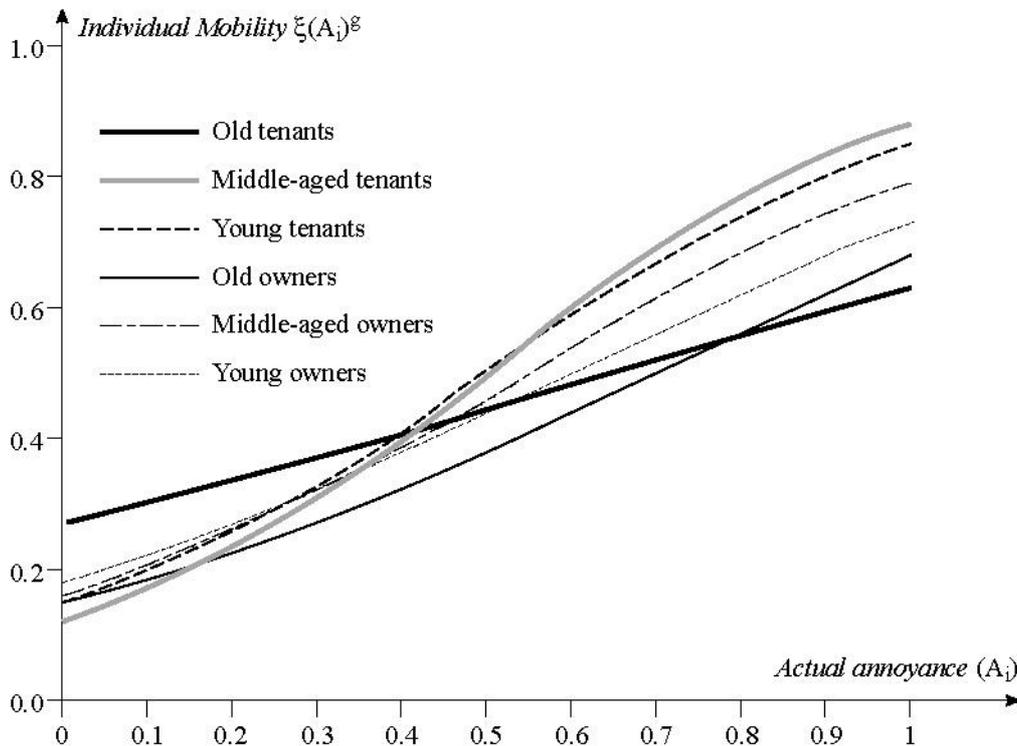
²Type 1: town centre; Type 2: dense inner urban; Type 3: less dense inner urban; Type 4: mixed suburb; Type 5: suburb; Type 6: public housing suburb; Type 7: mixed suburb with a dominance of public housing

The geometrical mean is a pessimistic aggregation operator (Tannier & Frankhauser, 2001): at the most, it gives results which are equal to the results obtained with the arithmetical mean. But the more the deviation between the aggregated values is high, the more the geometrical mean gives results inferior to the results given by the arithmetical mean. The fact that satisfied and very satisfied agents clearly underestimate the actual annoyance explains the general suitability of the geometrical mean. However, it may be interesting to introduce different aggregation operators for each type of agent. Indeed, fairly satisfied and unsatisfied agents slightly overestimate the actual annoyance, which could be modelled well with the quadratic mean.

Calibration of the parameters β^g and μ^g for calculating individual mobility $\xi(A_i)^g$

Regarding the mobility of the agents with respect to noise pollution, six types of agents have been defined on the basis of age, which is broken down into 3 modes (young people, middle-aged people and old people), and on the basis of housing occupancy status which is broken down into 2 modes (tenant or owner).

Figure 4: Variation of the individual mobility of the six types of agents



Using the survey data, the relationship between each annoyance value (0 - 0.237 - 0.53 - 1) and the mobility of each type of agent (high, medium or low) was explored. Such an exploration allows the determination of default values (also called “frame values”) for the

parameters μ^g and β^g . For example, considering the young owners, the exploration of the survey data gives the following information:

- When their actual annoyance is 0.237, their individual mobility is about 0.3
- When their actual annoyance is 0.53, their individual mobility is about 0.4
- When their actual annoyance is 1, their individual mobility is about 0.7¹

On this basis, it has been possible to determine the values of the parameters β^s and μ^s for which the logistic function gives results as near as possible to the “frame values” (figure 4).

Calibration of the parameters α and λ for calculating the Global Interest to Move M_{ij} and of the parameter $m^{(g^4)}$ for calculating the Dissatisfaction Level D_{ij}

The calibration of these parameters results purely from an empirical process. Indeed, no quantitative information about the two modelled phenomena can be obtained through the analysis of the survey data. Consequently, the only possibility is to determine realistic values for the parameters by means of an exploratory procedure, which involves carrying out a series of simulations for studying the effect of the variations of the value of the parameters on the results of the model. A value of a parameter is considered realistic if the simulation results obtained with the chosen value are themselves realistic with respect to the actual knowledge of the effect of noise annoyance on the residential migration process.

The application of this exploratory calibration procedure leads to the determination of the following values for the parameter $m^{(g^4)}$:

- 1.5 for the very sensitive agents,
- 1 for the agents of medium sensitivity,
- 0.8 for the agents of low sensitivity.

Concerning the α and λ parameters of the logistic function representing the Global Interest to Move, two pairs of values produce realistic simulation results.

- o With $\lambda = 10$ and $\alpha = 0.5$

$$\text{if } \sum_{j=1}^n D_{ij} = 0 \text{ then } M_{ij} = 0.007$$

$$\text{if } \sum_{j=1}^n D_{ij} = 0.5 \text{ then } M_{ij} = 0.5$$

$$\text{if } \sum_{j=1}^n D_{ij} = 0.9 \text{ then } M_{ij} = 0.98$$

- o With $\lambda = 5$ and $\alpha = 0.4$

¹ The young owners characterised by an actual annoyance of 0 are not numerous enough to determine a statistically representative rule.

$$\text{if } \sum_{j=1}^n D_{ij} = 0 \text{ then } M_{ij} = 0.12$$

$$\text{if } \sum_{j=1}^n D_{ij} = 0.5 \text{ then } M_{ij} = 0.62$$

$$\text{if } \sum_{j=1}^n D_{ij} = 0.9 \text{ then } M_{ij} = 0.92$$

The simulation results obtained with the second pair of values (5 and 0.4) belong to a smaller interval than the others. Moreover, the results obtained are clearly higher with the pair (10 and 1.5) except when considering high input data. However, it seems rather difficult to prefer one pair of parameters over the other one because of the lack of knowledge concerning the modelled phenomenon.

3.2 Analysis of the results obtained with SimNoise

The results obtained are always consistent with the survey results and, more generally, with the actual knowledge in the field of urban noise annoyance.

Table 1 presents the final results given by the model (*i.e.* the Aggregated Propensity to Move) for an agent characterised by a medium sensitivity to traffic noise ($m^{(g^4)} = 1$) and being moderately satisfied with his/her residential neighbourhood ($g_2 = 2$).

On one hand, the Aggregated Propensity to Move varies mainly according to the noise exposure level (in the order of about 0.3 to 0.5). Such variations are consistent with known reality: the noise environment is the first order factor which influences annoyance and the mobility of the agents.

On the other hand, the variation of the results with respect to the type of neighbourhood is fairly weak (lower than 0.1). Indeed, for a given noise level, the results can vary greatly if both the frequencies of each type of agent in each neighbourhood and the individual probability of moving differ significantly. Otherwise, compensation between the values occurs, leading to non-differentiated aggregated results. In the actual case, even if the frequencies differ greatly, the values of ω^g (Individual Propensity to Move) do not. The analysis of the survey data confirms the consistency of weak variations in the probabilities with respect to the type of neighbourhood.

Table 1: Probability of moving (Ω) for the agents characterised by medium sensitivity to traffic noise and being rather satisfied with their neighbourhood of residence

($\lambda = 10$ and $\alpha = 0.5$)

		Noise exposure level							
		Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	Level 7	Level 8
Type of neighbourhood	Type 1	0,18	0,19	0,20	0,24	0,26	0,30	0,31	0,46
	Type 2	0,17	0,17	0,19	0,23	0,25	0,29	0,29	0,43
	Type 3	0,17	0,17	0,19	0,23	0,25	0,29	0,30	0,44
	Type 4	0,17	0,17	0,19	0,23	0,25	0,29	0,30	0,44
	Type 5	0,17	0,17	0,19	0,23	0,25	0,29	0,29	0,43
	Type 6	0,19	0,20	0,21	0,25	0,26	0,30	0,31	0,45
	Type 7	0,18	0,19	0,20	0,25	0,26	0,31	0,32	0,47

Table 2 presents the results obtained for a given type of neighbourhood and twelve types of agents.

Table 2: Probability of moving (Ω) for the agents living in neighbourhood type 4

		Noise exposure level							
		Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	Level 7	Level 8
LOW SENSITIVITY $m^{(g^4)}=0.8$	not satisfied	0,2	0,2	0,2	0,3	0,3	0,3	0,3	0,5
	moderately satisfied	0,2	0,2	0,2	0,2	0,3	0,3	0,3	0,4
	satisfied	0,2	0,2	0,2	0,2	0,2	0,3	0,3	0,4
	very satisfied	0,1	0,1	0,2	0,2	0,2	0,3	0,3	0,4
MEDIUM SENSITIVITY $m^{(g^4)}=1$	not satisfied	0,2	0,2	0,2	0,3	0,3	0,3	0,3	0,5
	moderately satisfied	0,2	0,2	0,2	0,2	0,3	0,3	0,3	0,4
	satisfied	0,2	0,2	0,2	0,2	0,3	0,3	0,3	0,4
	very satisfied	0,1	0,1	0,2	0,2	0,2	0,3	0,3	0,4
HIGH SENSITIVITY $m^{(g^4)}=1.5$	not satisfied	0,2	0,2	0,2	0,3	0,3	0,4	0,3	0,8
	moderately satisfied	0,2	0,2	0,2	0,3	0,3	0,4	0,4	0,5
	satisfied	0,2	0,2	0,2	0,2	0,3	0,3	0,3	0,6
	very satisfied	0,1	0,1	0,2	0,2	0,2	0,3	0,3	0,6

The probabilities of moving are in general rather low, which seems realistic: people do not move easily and the spatial inertia of residential locations is generally high. The difference between agents of low sensitivity and medium sensitivity is very low: the level of sensitivity to traffic noise has an influence only when it is high.

From a more general point of view, not obtaining a unique value of migration probability (Ω) for each type of spatial unit may seem surprising. Actually, for this first application of the

SimNoise model, the aggregated probability of moving (Ω) is calculated on the basis of the aggregation of the individual probability of moving ω^g and considers only two individual variables: age and housing occupancy status (*formula 20*).

$$\Omega_i^{g_2, g_4}(h_1, h_2) = \sum_{g_3=1}^3 \sum_{g_1=1}^2 f^{(g_1, g_3)}(h_2) \times \omega_i^{(g_1, g_2, g_3, g_4)}(h_1) \quad (20)$$

This choice can be explained by several reasons. Firstly, considering the fact that the data sample does not allow the calculation of $f^{(g)}(h_2)$ when taking into account the four individual variables (g_1, g_2, g_3, g_4), we chose not to integrate the two variables “*sensitivity to traffic noise*” (g_4) and “*satisfaction with respect to the neighbourhood of residence*” (g_2) in the calculation of the aggregated probability of moving (Ω) because of their subjective nature. Secondly, the number of individuals of each type g_1 (housing occupancy status) and g_3 (age) can be easily obtained via census data or other official data sources, which is not the case for the variables (g_2) and (g_4). From a decision making point of view and also when considering the application of the *SimNoise* model to cities other than Besançon, it seems more judicious to eliminate those variables that cannot be quantified without further specific surveys.

Moreover, such a methodological choice offers two interesting opportunities.

- 1) Concerning the variable (g_2) “*satisfaction with respect to the neighbourhood of residence*”, it would be possible to apply a unique value of satisfaction to each segment of a road. Thus, an aggregated satisfaction would be introduced instead of individual satisfaction.
- 2) The variable (g_4) “*sensitivity to traffic noise*” gives an interesting indication of the extent to which there is variability in the results generated by the model. It aids in the interpretation of the results obtained because its meaning is close to that of a confidence interval.

Conclusion

The proposed general probabilistic modelling of intra-urban spatial dynamics presents a way to explicitly take into account the behaviour of agents on a microscopic level of analysis in a dynamic model stemming from synergetics. From an epistemological point of view, the introduction of microscopic behaviours is all the more interesting because the applications of modelling approaches in geography that stem from physics always consider urban dynamics on a macroscopic level.

Apart from such theoretical considerations, the development of the *SimNoise* model illustrates the real possibility of applying this general modelling approach to a concrete case. Hence, the

attraction of the presented approach is that the better the agents' behaviour is known, the more easily the model can be improved. From this point of view, the approach promotes the exchange of ideas between those with knowledge on a particular topic and researchers who deal with more theoretical and methodological questions.

Of course, supplementary work is required to improve the calibration of the *SimNoise* model, to explore its simulation capacities and to test a range of scenarios... It would also be interesting to go deeper into the modelling approach and the analysis of the thresholds that characterise the considered phenomena. For example, the influence of the variable “*housing occupancy status (owner or tenant)*” occurs only at low noise levels, but the actual version of the *SimNoise* model does not take into account the existence of such a threshold. The use of logistic functions in the formalisation of the model is well adapted for this. Another possible field for improvements in the model is the introduction of three supplementary spatial variables characterising the segments of a road:

- the *type of the road*, which determines the nature of the traffic flow
- the *daily rate of traffic flow*
- the *quality of building soundproofing*.

Indeed, as we explained previously, these three variables also influence the noise annoyance of the individuals as does the noise exposure level.

Finally, it would be interesting to try to improve the *SimNoise* model, firstly as a decision making tool allowing the simulation of noise annoyance associated with planning projects, and secondly to revisit the general modelling approach based on the experience of the application of the *SimNoise* model.

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