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Discrete Choice Modelling in a Context of Spatial Choice Behaviour : A Survey

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Abstract

The primary aim of this paper is to review the fundamental principles of the technique of discrete choice modelling applied to spatial choice behaviour. In particular, two major approaches are distinguished: static and dynamic models.

The most well-known static discrete choice model is the multinomial logit (MNL) model. This model offers a computational advantage that is unmatched by any other static model but suffers from the "independence from irrelevant alternatives" (IIA) axiom. To circumvent this problem, researchers have developed a number of non-IIA choice models such as the general extreme value model, the nested MNL model and the elimination-by-aspects model. At the same time a new modelling approach came to the fore, called decompositional multiattribute preference/choice model. This approach differs from conventional discrete choice models in that the preferences or choice are derived from hypothetical instead of actual choice alternatives. The method offers the advantage of making context-free estimates of the model's parameters which in turn produces somewhat more accurate predictions. Dynamic discrete choice models take account of the time factor in the choice analysis. Most dynamic extensions of static discrete choice models evolve around the problem of how to deal with structural and spurious state dependence ? A wide variety of dynamic models exists, but the number of applications is rather restricted.

Contents

Introduction

Scientists have always been interested in trying to predict human choice behaviour. This is because when individuals are asked to make a choice among several alternatives, they often experience uncertainty and show inconsistent behaviour. An important explanatory reason is that people are often not sure which alternative they should choose in order to gain the maximum satisfaction or utility, nor do they always select the same alternative under seemingly identical conditions. In order to account for these observed discrepancies choice behaviour is viewed as a probabilistic process.

Historically, psychologists, like Thurstone (1927) and Luce (1959) first made use of probabilistic choice models in an attempt to characterize different patterns of individual choice behaviour. Later, economists, beginning with Block and Marschak (1960), Marschak (1960) and McFadden (1968) developed such models that could pass for an econometric representation of utility maximizing behaviour. In the 1970s, conventional discrete choice models came to the fore (see e.g. Bahrenberg *et al.*, 1984). This branch of analysis is compatible with utility maximizing behaviour, but imposes an explicit discrete character to the choice variables instead of a continuous one. Discrete choices are defined as decisions taken by individuals among a finite set of discrete alternatives. As the alternatives and the choice makers are usually distributed over space, a large number of applications of traditional discrete choice modelling can be found in spatial behaviourial analysis: e.g. choice behaviour with respect to transportation routes and modes, residential and work location, college-choice, shopping and retailing, recreational trips, labour force participation, and industrial location and relocation.

The numerous applications of discrete choice models to spatial problems clearly points out the advantages of the technique but it also poses the question whether the underlying theoretical considerations remain valid in the various spatial applications. Over the past ten years in the work of Ben-Akvia (1973), McFadden (1974, 1976b, 1984), Lerman (1975), Manski (1977), Daganzo (1979), Horowitz (1980b, 1985), Heckman (1981a), Anas (1982), Wrigley (1982, 1985, 1986), Longley (1984a, 1984b), Timmermans (1984a, 1984c), Louviere (1988a, 1988b, 1988c), any many others, significant progress has been made in the field of choice theory and spatial choice models. In this paper we would like to review the fundamental principles of spatial choice modelling. The paper is organized as follows: in section 1 an effort is made to classify choice models according to different characteristics. Section 2 reviews the theory of the static discrete choice model and pays special attention to its various spatial applications and the comparison of the two most commonly used static spatial choice models. Section 3 presents an overview of dynamic approaches to spatial choice modelling. Finally, a number of conclusions are drawn.

1 Classification of choice models

A study of individual choice behaviour requires four primary ingredients (Ben-Akiva and Lerman, 1985, p. 32):

- (i) definition of de choice makers,
- (ii) description of the set of alternatives available to the choice makers known as choice set definition,
- (iii) description of the observed attributes of alternatives, and,
- (iv) selection of the decision rule.

First, the *choice maker* is an agent or actor whom performs a choice operation according to a fixed rule. The actor can be a single person, a group of individuals or even an organization.

The fact that each individual handles the choice problem in a different way and has a different perception of the reality, poses a number of problems. It makes that a choice problem is influenced by the choice maker's own subjective filtering of the environment, his or her aspiration and information level, value system and so on (Timmermans and Golledge, 1990, p. 312). Therefore, though we are ultimately interested in predicting aggregate behaviour, we cannot leave aside those individual differences.

Second, by definition a choice is made from a *set of alternatives*. Most spatial choices are made from large sets of possible alternatives. For instance, the number of places in a medium-sized city where a firm might choose to set up business can easily run in the hundreds. This makes it hard to consider all possible alternatives for a given problem to obtain the so-called 'universal set of alternatives'. This set conceivably extends well beyond the actual range of consideration of the decision maker. Instead a portion of the universe of alternatives is considered. This individual choice set consists of all alternatives that are both feasible to the decision maker and known during the decision process. The possibility of adding an alternative to the choice set depends upon a variety of constraints such as time availability, monetary resources and the lack of information. However, a misspecification of the choice sets will lead to an incorrect setting of the parameters of the utility function and incorrectly predicted choice probabilities. Thill (1992, p. 377) argues that quite a number of choice studies set up their choice sets on a basis of prespecified and rather arbitrary criteria and he suggests various approaches to tackle the problem of choice set specification. The proposed methods[1] differ in term of behavioural realism, incorporation of uncertainty, data and computation requirements and the potential of transferring the choice results from one problem to another.

[1] These methods include (i) Burnett and Hanson's method of decomposition of the decision making process into a choice-set generation subproblem and a choice generation subproblem; (ii) the simulated space-time prism that emphasizes the contraining nature of the decision environment and derives the set of feasible alternatives by means of simulation; (iii) Manski's random choice-formation model whereby the choice-set generation process is described by a probabilistic model; (iv) the information processing and competing destinations model; and (v) Meyer's learning model that copes with information gathering and constant updating to generate the choice set.

Third, the attractiveness of an alternative is expressed by a large, but finite set of observed or assumed *attribute values*. Each attribute value gives to the choice maker a certain amount of utility or appreciation for the alternative. Some of the attributes are of a quantitative nature, others are truly qualitative. When all separate attribute values of utility are combined the total amount of utility for an alternative is obtained. Timmermans and Borgers (1985b, p. 4) point out that choice models may be distinguished according to the *combination rule* into (i) compensatory choice models, and (ii) non-compensatory choice models.

A compensatory choice model assumes that the total utility of an alternative is the result of a (partial) compensation of a low evaluation of one of its attributes by the relatively high evaluations of one or more of the remaining attributes. In a non-compensatory choice model the choice alternatives are evaluated on an attribute-by-attribute basis. The smoothening or small trade-offs of attributes values does not exist.

On the basis of the alternative's total amount of utility alternatives can be ordered and a preference function can be found. The preference function is called deterministic (structural or systematic) if the decision-maker always assigns the same amount of utility to the same alternative. In other words, the utility level of the alternative is completely determined by its known attributes. When this is not the case, e.g. when random factors also influence the utility level of the alternative, the preference function is called stochastic. The alternative is said to have a deterministic utility component and a random utility component.

Fourth and finally, when making a choice out of a set of alternatives a *decision rule* is needed. The decision rule translates the preference function to the actual choice behaviour. Following Domencich and McFadden (1975) the preference of the choice maker among the alternatives is represented by an objective function, termed a utility function. The utility function is assumed to capture the choice maker's characteristics and the alternative's attributes. It is most common to assume that the choice maker is an utility maximizer. Therefore, if the preference function is deterministic the alternative that the choice maker perceives to have the greatest utility (or preference scale value) is chosen. In this case the decision rule is also deterministic. When, however, random components are present, the preference function is stochastic and the decision rule probabilistic. This means that the choice problem is not viewed to say which alternative is chosen but only to point out what the probability will be that the alternative is preferred over all others. The actual choice model will depend upon the *(joint) distributional assumption(s)* of the random utility component(s) of the preference function.

Most choice models are distinguished on the basis of their distribution assumptions made on the random term. Other distinctions can be based on the number of decision-makers (one individual or a group), the estimation level (individual or aggregate), the type of decision problem (single choice or multiple choice), the time dimension (static or dynamic), the information and knowledge level (certainty or uncertainty) and the choice situation or design (revealed or stated).

Perhaps it is useful to comment on the above mentioned distinctions used to characterize different choice models.

The *number of decision-makers* involved in the choice problem is rather straightforward. Most choice models are concerned with only one individual choice-maker. He or she chooses between the alternatives according to his or her own perception. It can however be possible that more than one person, e.g. a group of decision-makers, is involved with the choice making. In that case it is clear that as the number of participants in the decision making process increases the more complex the choice making will be. The actual decision will then not represent the choice of any specific individual, but is viewed as a compromise moulded by internal discussions and consultations whereby the participants are often brought into line through a system of bargaining.

The *estimation level* refers to whether the actual choice is made on an individual level, that is to say estimated for each individual separately, or on an aggregate level. Usually the data collected for the choice problem will determine the estimation level (see also Hartman, 1982).

By the *type of decision problem* is meant whether the choice model predicts a single choice behaviour or a multiple choice behaviour. In a model of single choice behaviour the emphasis is put on the prediction of the probability that a single alternative will be chosen from an individual's choice set. In a model of multiple choice behaviour the aim is to predict the choice probability of a combination or sequence of choice alternatives.

When taking into account the *time dimension* choice models can be viewed as static or dynamic. While static models are only concerned with uncovering the mechanism underlying the choice behaviour, dynamic choice models explicitly account for the changes in the choice behaviour over time. In other words dynamic models pay special attention to the effects of past experience on choice behaviour (adaptive behaviour).

The *information and knowledge level* determines whether the decision making in a choice model takes place under conditions of certainty (riskless choice) or under conditions of uncertainty (choice making under risk). In a riskless choice situation the decision-maker has full knowledge and information on the outcome of the choice decision, whereas in a choice making under risk this is not the case. The probability distribution governing the choice is assumed known but the decision-maker is unable to assess its outcome.

Finally, choice models can differ when the *choice (preference) situation* is altered. Two important variations exist: revealed choice models and stated choice models. Revealed choice models are models based on choices and decisions that have actually been made in the real world. Therefore, emphasis is placed on the observed choice behaviour and typically information on the reported characteristics of the alternatives in the choice set is used. In stated choice models the characteristics of the alternatives in the choice set are predefined so that a number of hypothetical or experimental choice situations (designs) are created. The respondent is then asked to make a ranking or rating or selection of a certain choice situation. Stated choice models always require a purpose-designed survey.

Following Timmermans and Borgers (1985b) and Timmermans and Golledge (1990) we will now focus on the major choice models that are used in spatial choice analysis. First, we will take a closer look at the static choice models. These include (i) the conventional discrete choice models, (ii) the compositional multiattribute attitude models, (iii) the decompositional multiattribute preference/choice models, and (iv) the hybrid evaluation models. Second, the dynamic choice models are reviewed.

2 Static choice models

2.1 Conventional discrete choice models

Beginning with McFadden's contribution (1976b) on choice analysis econometricians became interested in the problem of discrete choice. Discrete choices may be defined as decisions taken by individuals among a finite set of discrete alternatives. Conventional discrete choice models take for granted that the choice of the decision maker can actually be observed in reality. Choices are therefore considered as 'revealed' choices. The models of discrete choice (also called quantal or qualitative or revealed choice models) deal, not with questions of "how much", but with questions of "which", "when" or "where" (Anas and Moses, 1984, p. 547).

The most well-know applications of discrete choice models are in area of the spatial analysis. Excellent reviews by McFadden (1976b, 1984), Ortuzar (1982), Wrigley (1982), Anas and Moses (1984), Longley (1984b), Timmermans and Borgers (1985b), Fischer and Nijkamp (1985, 1987), Golledge and Stimson (1987), Timmermans and Golledge (1990), Anderson *et al.* (1992b), and others, mention the application of discrete choice techniques to problems of (i) travel demand analysis[2] whereby a traveller decides how to commute to work (e.g. by car, bus or train) or how to go shopping, (ii) choice of housing or residential location[3] whereby households choose the location or community in which to rent or buy housing or the type of housing to occupy, (iii) college-choice[4] whereby scholars choose the school or university to go to, (iv) shopping behaviour and retailing[5] whereby shoppers have to make a selection among

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[2] see e.g. Warner (1962), Lave (1970), Talvitie (1972), McFadden (1973, 1978, 1981), Ben-Akiva (1973), Watson and Westin (1973), Wigner (1973), McFadden and Reid (1974), Watson (1974a, 1974b), Domencich and McFadden (1975), Richards and Ben-Akiva (1975), Ben-Akiva and Richards (1976), Ben-Akiva and Atherton (1977), Parody (1977), Hausman and Wise (1978), Adler and Ben-Akiva (1979), Ben-Akiva and Lerman (1979, 1985), Cambridge Systematics Inc. (1979, 1984), Horowitz (1979, 1980a, 1980b, 1985), Oum (1979), Train (1980, 1986), Sasaki (1982), Hensher (1983), Manski (1983), McDonald (1983), Ortuzar (1983), Brouwer and Nijkamp (1984), Halperin and Gale (1984), Thobani (1984), Koppelman and Pas (1985), Fischer (1986), Blauwens and Van de Voorde (1988), Ettema (1993) and Hunt and Teply (1993).

[3] see e.g. Quigley (1973, 1976, 1985), Friedman (1974), Pollakowski (1975), Lerman (1975, 1977), Li (1977), Hensher (1978), McFadden (1978), Lerman (1979), Anas (1981, 1982), Ellickson (1981), Van Lierop (1981, 1985, 1986), O'Brien (1982), Hensher and Taylor (1983), Onaka (1983), Onaka and Clark (1983), van der Knaap and Ament (1983), Anas and Chu (1984), Falchi and Mariano (1984), Gabriel and Rosenthal (1984), Longley (1984), Van Lierop and Nijkamp (1984), Van Lierop and Rima (1984, 1985), Veldhuisen (1984, 1985), Clark and Onaka (1985), Aufhauser, Fischer and Schönhofer (1986), Clark and Van Lierop (1986), Fischer and Aufhauser (1986, 1988), Anderstig (1987), Börsch-Supan (1987), Rouwendal (1988), Thill and Van de Vyvere (1989) and Molin, Oppewal and Timmermans (1994).

[4] see e.g. Miller and Radner (1970, 1974), Manski (1981), Kohn, Manski and Mundel (1976), Ritzen and Winkler (1977) and Linneman and Graves (1983).

[5] see e.g. Burnett (1973), Adler and Ben-Akiva (1976), Koppelman and Hauser (1978), McCarthy (1980), Gautschi (1981), Miller and Lerman (1981),

different stores they want to visit, (v) recreational behaviour[6] whereby people choose between different recreational trips, (vi) labour force participation[7] whereby workers choose among different job offers, (vii) choice of energy[8] whereby a selection of heating systems needs to be made, (viii) choice for differentiated consumer products[9], and (ix) choice of industrial location[10]. It is only within the last decade that discrete choice techniques are being applied to the problem of industrial and retail store (re)location. In this case a firm decides in which of a number of possible locations (regions, suburban municipalities or shopping centres) it should establish business.

Let us now focus on how the conventional discrete choice models may be derived. Suppose we summarize a choice model mathematically as follows (see also Borgers, 1992):

Southworth (1981), Landau, Prashker and Alpern (1982), Lerman and Liu (1984), Timmermans (1984c), Roy (1985) and Timmermans, Borgers and van der Waerden (1991, 1992).

[6] see e.g. Leven and Mark (1977), Peterson *et al.* (1983), Lin *et al.* (1988), Borgers, van der Heijden and Timmermans (1989) and Dellaert and Timmermans (1992).

[7] see e.g. Boskin (1974), Schmidt and Strauss (1975), Evers and Van der Veen (1983), Fischer and Maier (1984, 1986), Maier and Fischer (1985), Evers (1989) and Hughes and McCormick (1989).

[8] see e.g. Hartman (1982), Quigley (1984), Dubin (1986) and Kasanen and Lakshmanan (1989).

[9] see e.g. Anderson, de Palma and Thisse (1989, 1992a, 1992b) and Anderson and de Palma (1992a, 1992b).

[10] see e.g. Miller and Lerman (1979), Oster (1979), Erickson and Wasylenko (1980, 1981), Carlton (1983), Leonardi (1983), Leonardi and Tadei (1984), Blackley (1985), Lee and Cohen (1985), Lugar and Shetty (1985), Hayashi, Isobe and Tomita (1986), Hansen (1987), Lee, Choe and Pahk (1987), Boots and Kanaroglou (1988), de Palma (1988), White (1988), Das (1989), Henley *et al.* (1989), Lee (1990), McConnell and Schwab (1990), Coughlin, Terza and Arromdee (1991), Kriesel and McNamara (1991), Shukla and Waddell (1991), Anderson, de Palma and Hong (1992), Friedman, Gerlowski and Silberman (1992), Woodward (1992) and Sugiura (1993).

An individual choice maker i (= 1,..., I) determines from a universal set of alternatives C, in accordance with a number of constraints, his or her choice set $C_i \subseteq C$. This choice set consists of a number of mutually exclusive alternatives j (= 1, ..., J) and is denoted:

$$C_i = \{\text{alternative 1, alternative 2, ..., alternative J}\} \qquad [1]$$

The alternatives are characterized by the attributes k (= 1, ..., K). For the choice maker i the attribute k of alternative j represents a utility value denoted X_{ijk}. According to a combination rule the attributes values are put together to form the total amount of utility of the alternative denoted V_{ij}. The choice problem is to estimate the alternative's choice probability.

We know that choice makers choose the alternative that give them the highest utility. This means that if we correctly evaluate the different attributes of all given alternatives we can always indicate without any doubt which alternative the decision maker will select. If this were true, human choice behaviour would be very easy to model.

But can we suppose that the evaluation of the observed attribute values will remain constant over time and space, and what to do with unobserved attributes or known but not measurable attributes and with the effects of unobserved variations in the choice behaviour when all other factors stay identical ? It appears that the only valid solution, as noted by psychologists in the nineteen twenties, is to introduce a probabilistic mechanism to explain behaviourial choice inconsistencies. A probabilistic choice model could take into account pure random behaviour as well as errors due to incorrect perception of the attributes.

The probabilistic theories of preference differ with respect to the nature of the mechanism that is assumed to govern the choice. In the literature three approaches are distinguished: (i) the constant utility, (ii) the strict utility, and (iii) the random utility approach.

First, the constant utility approach (Luce, 1959; Luce and Suppes, 1965) treats the utilities of the alternatives as fixed. Instead of selecting the alternative with the highest utility a random element to the decision rule is introduced. The choice makers behave according to a probability distribution function *P* over the alternatives that includes the utilities as parameters.

Mathematically, the probability that a choice maker *i* will select an alternative *j* can be written as $P_i(j)$ or $P(j|C_i)$ with following properties:

$$0 \leq P(j|C_i) \leq 1 \qquad [2]$$

and

$$\sum_{j \in C_i} P(j|C_i) = 1 \qquad [3]$$

Second, the strict utility model (Luce, 1959; Debreu, 1960) can be considered as an extension of the constant utility approach. It states that the probability of choosing an alternative *j* is equal to the ratio of the utility of that alternative *j* to the sum of the utilities of all alternatives in the choice set of the decision maker *i*, or:

$$P(j|C_i) = \frac{U_{ij}}{\sum_{m \in C_i} U_{im}} \qquad [4]$$

The strict utility model is based on the so-called 'choice axiom' (see Luce, 1959 and 1977; Halldin, 1974). This states that if we remove a number of alternatives from a choice set, the relative choice probabilities from the reduced choice set will stay unchanged. In other words the choice probabilities will dependent only on the alternatives present in the choice set and are therefore independent of any other alternatives that may exist. This property is known as *independence from irrelevant alternatives* (IIA)[11]. A good review on the procedures to determine violations of the IIA property and proposals to remedy violations is given by Hensher and Johnson (1981, pp. 135-161). We will return to the IIA-property when dealing with the multinomial logit model.

It is also assumed that the utilities of the alternatives can be scaled and ordered as showed by Tversky's simple scalability property (1972a, 1972b). The ordering of the alternatives is independent of the choice set. This implies that if an alternative *j* is preferred to an alternative *m* in one context then *j* should always be chosen over *m* in any context. But it should also be true that if a choice maker is indifferent between *j* or *m* (of the same order) their choice probabilities must be equal. This assumption, however, is not valid in general as demonstrated e.g. in an experiment by Becker, DeGroot and Marschak (1963). They feel that random factors have a strong influence on choice behaviour. This leads us to the third approach.

The random utility approach (Thurstone, 1927; Manski, 1977; Yellott, 1977; Strauss, 1979) assumes that the utilities of the alternatives are not known with certainty. Therefore they are to be treated as random variables. This implies that the individual utility function can be divided into two (additive) parts: a deterministic component and a random utility component. This leads to:

$$U_{ij} = V_{ij} + \epsilon_{ij} \qquad [5]$$

Due to the randomness of the utilities the choice probability of an alternative *j* is

[11] The term "independence from irrelevant alternatives" is somewhat confusing in this present context. Block and Marschak (1960) suggest instead "irrelevance of added alternatives".

equal to the probability that the utility associated with that alternative j is greater than the utilities of all other alternatives in the choice set. Mathematically this can be written as follows:

$$P(j|C_i) = Pr\{U_{ij} > U_{im}; \forall m \neq j; j, m \in C_i\} \qquad [6]$$

Equation [6] results in that the choice problem is not viewed to say which alternative is chosen but only to point out what the probability will be that the alternative is preferred over all others. Therefore, the actual choice model will dependent upon the *distributional assumption* of the random utility component.

There are a number of possible interpretations of the random term. Anas (1982, p. 57) for instance mentions six different explanations:

(i) deterministic variations of preference,
(ii) stochastic instability of preference,
(iii) differences between perceived and realized utility values,
(iv) unobserved attributes of the choice alternatives,
(v) unobserved constraints on behaviour, and,
(vi) irrational behaviour.

The first two interpretations are not self-evident. By (i) is meant that individuals have a completely deterministic (homogeneous) preference structure. The random utility term is then introduced to capture the interindividual variations in utility which are assumed to be constant over time. Explanation (ii) refers to differences in the utility function due to time. In other words given the same choice conditions the actual choice can differ from period to period. The random term could account for the intraindividual variations (Fischer and Nijkamp, 1985, pp. 533-534).

The random utility approach will form the basis for the further development of the conventional discrete choice model. Let us now concentrate on making the random utility theory operational.

We start by rewriting equation [6] using equation [5]:

$$P(j|C_i) = Pr\{V_{ij} + \epsilon_{ij} > V_{im} + \epsilon_{im};\ \forall\ m \neq j;\ j,\ m \in C_i\} \qquad [7]$$

Rearranged this results in:

$$P(j|C_i) = Pr\{V_{ij} - V_{im} > \epsilon_{im} - \epsilon_{ij};\ \forall\ m \neq j;\ j,\ m \in C_i\} \qquad [8]$$

Suppose that the categorized or qualitative, nominal response variable is dichotomous, the choice set is then reduced to only two alternatives ($C_i = \{j, m\}$). This makes that $P(j|C_i) = 1 - P(m|C_i)$, and it also limits the number of disturbances to just two. Equation [8] states that to know or estimate $P(j|C_i)$, we need to know whether the total or cumulative probability of the difference in two V's (let $V_i = V_{ij} - V_{im}$) is greater than the difference in two ϵ's (let $\eta_i = \epsilon_{im} - \epsilon_{ij}$). If η_i is a continuous random variable equation [8] can be written as:

$$Pr\{V_i > \eta_i\} = F(V_i) = \int_{\eta_i=-\infty}^{V_i} f(\eta_i)d\eta_i \qquad [9]$$

whereby $F(.)$ is the cumulative distribution function and $f(.)$ the probability density function of the random variable. All random utility based discrete choice models differ according to the assumptions made on the cumulative probability distributions of the random term. So different distributions result in different random utility choice models having different properties (see table 1).

The binary (binomial) choice models are conceptually easy to derive and numerous applications can be found in the literature. However, it is fair to say that the choice set will usually consists of more than just two alternatives. In other words the response variable is polytomous. An important consequence is that it is not sufficient simply to specify a univariate distribution of the differences in the disturbances, like in the binary case (equation [9]), but we will have to characterize the complete joint distribution of all the disturbances.

Table 1: Classification of binary choice models according to the distributional assumption of the random term [12]

distribution of the random utility component	associated discrete choice model	leading monographs
uniform distribution	linear probability model (LPM) truncated LPM (tobit model)	Ross (1977), McCullagh and Nelson (1983), Aldrich and Nelson (1985) Tobin (1958), Amemiya (1973)
Cauchy distribution	arctan probability model	Aldrich and Nelson (1985)
normal distribution	binary probit model	Cox (1970), Finney (1971)
logistic distribution	binary logit model	Berkson (1944), Gumbel (1961)

Let $f(\eta_{i1},..,\eta_{ij},..,\eta_{iJ})$ denote the joint density function of the disturbance terms. The probability that $V_{i1} > \eta_{i1}$, .., $V_{ij} > \eta_{ij}$, .., $V_{iJ} > \eta_{iJ}$ will simultaneously (jointly) occur, is equal to:

$$F(V_{i1},\dots,V_{ij},\dots,V_{iJ}) = \int_{\eta_{i1}=-\infty}^{V_{i1}} \dots \int_{\eta_{ij}=-\infty}^{V_{ij}} \dots \int_{\eta_{iJ}=-\infty}^{V_{iJ}} f(\eta_{i1},\dots,\eta_{ij},\dots,\eta_{iJ})d\eta_{i1}\dots d\eta_{ij}\dots d\eta_{iJ} \qquad [10]$$

[12] There are some excellent reviews on the matter of binary choice models and analysis of binary data: see e.g. Domencich and McFadden, 1975, pp. 53-65; Amemiya, 1981, pp. 1483-1536; Cosslett, 1981, pp. 51-111; McFadden, 1984, pp. 1396-1403; Ben-Akiva and Lerman, 1985, pp. 59-99; Börsch-Supan, 1987, pp. 21-40; Collett, 1991; Cramer, 1991, pp. 5-42.

The calculation of this complex multiple integral forms an important drawback to the multinomial discrete choice models.

As in the binary case, the actual multinomial choice model depends on the distribution chosen for the random components. Two important cases are considered here: (i) the multinomial probit model, and (ii) the multinomial logit model.

2.1.1 The multinomial probit model

The multinomial probit (MNP) model specifies the distribution function of the random utility components as multivariate normal. Because the normal distribution seems the natural first choice probit models appeared already in early mathematical psychological writings (see e.g. Thurstone, 1927; Gaddum, 1933; Bliss, 1934). However, its computational difficulty made it unusable until Finney (1947, reprinted in 1971) published his monograph on the binary probit analysis. Later important contributions are those from Aitchison and Bennett (1970), Dutt (1976), Manski and Lerman (1977), Daganzo, Bouthelier and Sheffi (1977), Hausman and Wise (1978), Daganzo (1979), Daganzo and Sheffi (1982) and Amemiya (1985).

Daganzo (1979, p. 17) defines the MNP model as a random utility model in which the error terms have a joint multivariate normal distribution with zero mean and an arbitrary variance-covariance matrix (Σ_ϵ). This specification is attractive because it can capture all possible correlation patterns among the disturbances. However, the computational difficulties that arise from this theoretical property makes the MNP model less useful. When the multivariate normal distribution is introduced in equation [10] the determination of the choice probabilities requires a complex numerical calculation of a multiple integral[13].

The complexivity of the problem can be reduced by imposing some assumptions or restrictions on the model. Rouwendal (1988, p. 23) argues that to a large extent the complexity of the MNP model depends upon the way in which the covariance matrix is filled. If we assume that the error terms ϵ_i are independent and identically normally distributed the matrix Σ_ϵ is diagonal with all diagonal elements being identical. This case is however often judged to be unrealistic.

Amemiya (1985, p. 308) and Börsch-Supan (1987, p. 24) propose to limit the number of alternatives in the choice set in order to reduce the complexivity of the problem. This was first put to the test by Hausman and Wise (1978, pp. 403-426) in their analysis on modal choice. They have made a thorough investigation of the trichotomous probit model (three-alternative case) and noted that when the number of choice alternatives is small ($J \leq 3$) direct numerical integration is still practical, but impractical for choice sets with five and more alternatives. This important drawback of the probit model led to the development of alternative choice probability calculation methods. We mention, without pursuing the subject any further, the Monte Carlo simulation method (Lerman and Manski, 1981), the numerical approximation method (Clark, 1961; Bouthelier, 1978) which claims it can handle as many as ten alternatives at a time, and the method of simulated moments (McFadden, 1989).

The fact that the use of normally distributed error terms poses a number of practical problems leaves room for alternative specifications such as the multinomial logit model.

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[13] The choice probability can be written as follows:
$P(j|C_i) = \int_{-\infty}^{+\infty} \left(\prod_{m \neq j} \int_{-\infty}^{V_{ij}-V_{im}+\epsilon_{ij}} N(\epsilon_i|0,\Sigma)\, d\epsilon_{im}\right) d\epsilon_{ij}$ where N(.) denotes a multivariate normal density function with zero mean and variance-covariance matrix Σ_ϵ.

2.1.2 The multinomial logit model

The multinomial logit (MNL) model is the result if we assume that the random elements in utility are (i) independently, (ii) identically and (iii) Type I extreme value distributed. The latter distribution is also called double exponential, log-Weibull, Gumbel or Gnedenko distribution.

Independently and identically distributed (IID) error terms imply that the variances of the random components of the utilities are equal (homoscedasticity) and that all covariances are zero. If IID can be defended then a suitable distribution is the Type I extreme value distribution which in terms of the ϵ_{im} is defined as follows (Johnson and Kotz, 1970, p. 272):

$$Pr\ (\epsilon_{im} \leq \epsilon_i) = \exp\{-\exp(-(\epsilon_i - \mu)/\lambda)\} \qquad [11]$$

with μ = location parameter
λ = scale parameter ($\lambda > 0$)
mean = $\mu + 0.57722\ \lambda$
variance = $1.64493\ \lambda^2$

The distribution in its standard form ($\mu = 0$ and $\lambda = 1$) results in that the disturbances have a common mean of 0.57 (Euler's constant) and standard deviation of 1.28. Equation [11] is then reduced to:

$$Pr\ (\epsilon_{im} \leq \epsilon_i) = \exp(-\exp -\epsilon_i) = e^{-e^{-\epsilon_i}} \qquad [12]$$

with following probability density function:

$$f(\epsilon_i) = \exp\{-\exp(-\epsilon_i) - \epsilon_i\} \qquad [13]$$

The name 'extreme value' refers to the property that it is the limiting distribution of the maximum of n IID variables as n approaches infinity. Because the choices are made according to maximum utility the extreme value distribution seems a proper distribution. In its standard form it is not very different from a normal distribution with the same mean and variance.

Let us recapitulate for a moment. If we take equation [8] and rearrange this, we get the following result:

$$P(j|C_i) = Pr\,\{\epsilon_{im} - \epsilon_{ij} < V_{ij} - V_{im};\ \forall\, m \neq j;\, j,\, m \in C_i\} \qquad [14]$$

This is equal to:

$$P(j|C_i) = Pr\,\{\epsilon_{im} < \epsilon_{ij} + V_{ij} - V_{im};\ \forall\, m \neq j;\, j,\, m \in C_i\} \qquad [15]$$

Since we assume that each ϵ_{im} is IID, the probability of choosing an alternative j, $P(j|C_i)$, can be written as the product of M-1 terms (product rule):

$$P(j \mid C_i) = \prod_{m=1, m\neq j}^{M} Pr\,\{\epsilon_{im} < \epsilon_{ij} + V_{ij} - V_{im};\ \forall\, m \neq j;\, j,\, m \in C_i\} \qquad [16]$$

Using equation [12] and [16] the probability that an alternative j is chosen, is given by:

$$P(j \mid C_i) = \prod_{m=1, m\neq j}^{M} \exp\,\{-\exp - (\epsilon_{ij} + V_{ij} - V_{im})\} \qquad [17]$$

It can be shown that equation [17], after some elaborate calculations (using equation [10]), reduces to a logit model. The mathematical derivation can be found in e.g. Hensher and Johnson (1981, pp. 39-42), Maddala (1983, pp. 60-61), Ben-Akiva and Lerman (1985, pp. 104-106) and Cramer (1991, pp. 50-51). The result is:

$$P(j|C_i) = \frac{1}{1 + \exp(V_{im} - V_{ij})} \quad \text{in the binary case, and} \qquad [18]$$

$$P(j|C_i) = \frac{\exp(V_{ij})}{\sum_{m \in C_i} \exp(V_{im})} \quad \text{in the multinomial case.} \qquad [19]$$

The first to advocate the (binary) logit model was Berkson (1944, 1951). He defined the "logit" as a 'logistic probability unit'. By this is meant the natural logarithm of the odds, or log odds. The odds indicate the relative probability of choosing for one or another alternative on some variable of interest. Applied to the choice of location, the logit model expresses the conditional log odds of location X as a linear function of a set of explanatory variables. The model is similar to the linear regression model except that the response is the log odds rather than a metric dependent variable.

Theil (1969) generalized the binary logit model to a multinomial case. This opened up the field for other researchers to exploit further possibilities. Through the work of Daniel McFadden (1968, 1974, 1976a, 1976b, 1978, 1981, 1984, 1987) the MNL model became extensively applied to empirical studies of choice problems. At first this mainly confined to the problem of modal split but to date, the MNL model is, without any doubt most widely used in all branches of regional analysis. Further theoretical important contributions on the MNL model are those from Parks (1980), Cavanagh (1982), Hausman and McFadden (1984) and Small (1987).

Let us now focus on some of the properties of the multinomial logit model. To bring out these properties we return to equation [19]. This states that the probability that an alternative *j* is chosen, is equal to the ratio of the associated deterministic utility of that alternative (V_{ij}) to the sum of the deterministic utilities of all other alternatives (V_{im}). This MNL model has the following properties (see also Anderson *et al.*, 1992, pp. 42-45; Borgers, 1992, pp. 7-8):

(i) the probability to select alternative *j* will increase if its deterministic utility increases or if the deterministic utilities of all other alternatives decreases, and vice versa.

(ii) the choice probability will not dependent upon the absolute value of the deterministic utilities. Adding to or subtracting from all deterministic utilities a random number (x) does not affect the choice probability. This can be shown as follows:

$$P(j|C_i) = \frac{\exp(V_{ij} + x)}{\sum_{m \in C_i} \exp(V_{im} + x)} \qquad [20]$$

which can be written as:

$$P(j|C_i) = \frac{\exp(V_{ij})\ \exp(x)}{\sum_{m \in C_i} \exp(V_{im})\ \exp(x)} \qquad [21]$$

The fraction can be simplified by elimination of the term exp (x) in both the numerator and denominator. The result is the familiar logit model.

(iii) the ratio of the choice probabilities of any two alternatives is entirely unaffected by the deterministic utilities of any other alternatives. The odds ratio of choosing alternative *j* over alternative *l* is defined as:

$$\frac{P(j|C_i)}{P(l|C_i)} = \frac{\dfrac{\exp(V_{ij})}{\sum_{m \in C_i} \exp(V_{im})}}{\dfrac{\exp(V_{il})}{\sum_{m \in C_i} \exp(V_{im})}} = \frac{\exp(V_{ij})}{\exp(V_{il})} = \exp(V_{ij} - V_{il}) \qquad [22]$$

By taking the logarithm of equation [22] we find the *log odds ratio* of the two alternatives:

$$\log(\frac{P(j|C_i)}{P(l|C_i)}) = V_{ij} - V_{il} \qquad [23]$$

This states the remarkable fact that if any two alternatives are compared with another this is exclusively done on the difference in the characteristics of the two alternatives concerned (V_{ij} - V_{il}), independent of the attributes of all other alternatives and independent of the number of alternatives in the choice set. The log odds ratio is therefore unaffected by the addition or deletion of alternatives in the choice set. This property is known as *independence of irrelevant alternatives* (IIA) and it is responsible for making the MNL model 'context independent'. This means the model ignores the effect of similarities among alternatives on the probability of choice.

The IIA-property is attributed to McFadden (1974, p. 109) and is obviously in accordance with Luce's (1959) choice axiom. Domencich and McFadden (1975, p. 69) view the IIA-property as both the principal strength and the principal weakness of the MNL model. It is a strength because once the utility function parameters have been established new alternatives can be introduced to or existing alternatives removed from the choice set without the re-estimation of the model. One simply adds or drops the alternative to or from the denominator of equation [19] for each alternative. This procedure is possible because the odds ratio is unaffected by it. Merely on computational grounds the logit model is preferred to the probit model. It is a weakness because IIA can lead to unacceptable results since it also implies to highly relevant alternatives. Furthermore, alternatives are also required to be perceived as completely distinct and independent. The definition of 'distinct' is complex. It revolves around the problem to what extent alternatives can be considered as similar or dissimilar. The two classical examples to illustrate this problem are Debreu's (1960, pp. 186-188) case of the recordings of the same concerto with a live performance and McFadden's (1974, p. 113) case of the red and blue buses.

The following application translates the effects of the IIA-property to the choice of business location. Consider the choice between a location in the city centre or a location in the suburban region. For simplicity, we assume that the relative odds of two location sites are equal. Now we introduce a third location which is a very close substitute for the existing central location (e.g. in the same street but directly opposite to it). The task is to forecast the choice probability of this 'new' alternative. Intuitively, we would expect that the new distribution would be something like 50 % for the suburban location versus 50 % for both central locations. But according to condition [23], the log odds ratio of the suburban location versus the central location has to stay constant regardless of the number or the attributes of any other alternative. The 'new' alternative is therefore to gain its share of the market by a proportional reduction of the probabilities of all possible location sites, forcing a distribution of 33 % for all three alternatives. This is clearly implausible there it stands to reason that the existing central location will be much more affected by the introduction of the 'new' alternative than the suburban location. The paradox appears even more striking when it is understood that the probability of choosing the suburban location can be made arbitrarily small by considering a sufficiently large set of central locations with minor differences.

(iv) the cross elasticities of the choice probability of alternative j with respect to the attributes of any other alternative m ($\neq j$) is constant, that is independent of *j*.

We define the elasticity of the choice probability of alternative *j* for an individual *i* with respect to a change in the *k*th attribute as follows:

$$E_{X_{ijk}}^{P(j|C_i)} = \frac{dP(j|C_i)}{dX_{ijk}} \cdot \frac{X_{ijk}}{P(j|C_i)} \qquad [24]$$

If we assume that the deterministic utility for a choice maker *i* is a linear additive function of the various observable attributes *k* of alternative *j*, that is $V_{ijk} = \beta_k X_{ijk}$ and we substitute this in the MNL model defined under equation [19] the elasticity is found using the quotient rule for derivatives. After some calculations the result is:

$$E_{X_{ijk}}^{P(j|C_i)} = \beta_{jk}\, X_{ijk}\, \{(1 - P(j|C_i)\} \qquad [25]$$

Similarly we define the cross elasticity of the choice probability of alternative *j* with respect to an attribute of alternative *m* as:

$$E_{X_{imk}}^{P(j|C_i)} = \frac{dP(j|C_i)}{dX_{imk}} \cdot \frac{X_{imk}}{P(j|C_i)} \qquad [26]$$

which results into:

$$E_{X_{imk}}^{P(j|C_i)} = -\,\beta_{mk}\, X_{imk}\, P(m|C_i) \qquad [27]$$

Notice that in equation [27] the cross elasticity only depends on variables that are associated with alternative *m*. Hensher and Johnson (1981, p. 58) therefore conclude that cross elasticities with respect to a variable associated with an alternative *m* are the same for other alternatives. This property follows the IIA-property.

In conclusion, the MNL model offers a computational advantage that is unmatched by any other discrete choice model. This could well be one of the reasons for its extensive use to handle all kinds of decompositional choice problems. However, a major drawback of the MNL model are the restrictions it imposes on the choice behaviour. Implying that the choice probability of two seemingly similar alternatives is independent from one another is unacceptable (cfr. the IIA-property). In order to alleviate this weakness to a certain extent but making use of the computational convenience of the MNL model a number of different extensions can be found.

2.1.3 Non-IIA choice models

An important extension of the simple MNL model is an approach which is able to account for the *substitution effects* that arise from the correlation in the error terms of similar alternatives.

Following Borgers and Timmermans (1987, pp. 31-34) three classes of substitution models may be distinguished: (i) models which impose more general conditions on the variance-covariance matrix of the error terms[14], (ii) models which account for substitution effects by extending the simple MNL model formula[15], and (iii) models with a hierarchical or sequential decision

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[14] Examples are Nakanishi and Cooper's (1974) and Bultez and Naert's (1975) multiplicative competitive interaction (MCI) model; Williams' (1977, 1981) and Williams and Ortuzar's (1982) cross-correlated logit model; Daganzo, Bouthelier and Sheffi's (1977) and Daganzo's (1979) generalized probit model; Hausman and Wise's (1978) perceptual interdependence model; McFadden's (1978) generalized extreme value model; Daganzo's (1979) negative exponential distribution model; Kamakura and Srivastava's (1984) probit model.

[15] Examples are Gaudry and Dagenais' (1979) dogit model; Batsell's (1980, 1981, 1982) discrepancy model; Meyer and Eagle's (1981, 1982) weight-shifting model; Huber's (1982) cumulative logit model; Huber and Sewall's

structure[16].

Substitution effects and substitution models have widely been discussed in a number of reviews[17]. A thorough discussion of all different substitution models would lead us to far. Therefore, we would like to limit our discussion to just three, albeit, fundamental substitution models and refer the more interested reader to the specific references.

The models under consideration here are (i) the generalized extreme value model, (iii) the nested logit model, and (iii) the elimination-by-aspects model.

The generalized extreme value (GEV) model, proposed by McFadden (1978, 1981), permits a more flexible pattern of crossalternative substitution (like the probit model) and can computationally handle more than three alternatives at a time (like the logit model). The model is a generalization of a multinomial logit model which maintains the extreme value distribution but which allows for the dependence likely to exist between alternatives in a choice set[18].

(1982) model; Cooper and Nakanishi's (1983); Borgers and Timmermans' (1984) model; Batsell and Polking's (1985) extended logit model; Small's (1987) ordered logit model.

[16] Examples are Tversky's (1972a, 1972b) elimination-by-aspects (EBA) model and elimination-by-strategy (EBS) model; McFadden (1978) and Sobel's (1981) nested logit model; Gensch and Svestka's (1979) model; Recker and Golob's (1979) model; Tversky and Sattath's (1979) hierarchical-elimination-by-aspects (HEBA) model; Strauss' (1981) choice-by-feature (CBF) model; Hauser and Tversky's (1981) hierarchical balance model; Manrai and Sinha's (1989) elimination-by-cutoffs (EBC) model.

[17] see e.g. Currin (1982), Ortuzar (1982), Van Lierop and Nijkamp (1982), Wrigley (1982, 1985), Corstjens and Gautschi (1983), Wrigley and Longley (1984), Amemiya (1985), Fischer and Nijkamp (1985), Timmermans and Borgers (1985a, 1985b), Borgers and Timmermans (1987, 1991), Haynes, Good and Dignan (1988), Jain and Bass (1989), Manrai and Sinha (1989), Timmermans and Golledge (1990).

[18] The GEV cumulative distribution function is equal to $F(.) = \exp\{-G[\exp(-\epsilon_1),..., \exp(-\epsilon_J)]\}$ where G is a non-negative, homogeneous of degree $\mu > 0$

The basic idea is to relax the IID assumption by making use of an hierarchical tree structure to describe the choice process whereby the choice set is divided into a number of smaller subsets. This can be done by grouping or clustering into subsets of choices those alternatives that are more alike to each other (with a high correlation in the error terms) relative to the other alternatives. These in the choice subset so-called 'nested' alternatives have nonindependent error terms, thus the IIA-property does no longer hold and the model is said to be context-sensitive. Subsets may themselves be more or less similar to each other. This makes it possible that more than two levels of nesting can exist, thus hierarchically introducing similar and dissimilar alternatives on each level (Börsch-Supan, 1987, p. 43). This type of GEV model is the most practical special case of all GEV models and is called the nested (structured or hierarchical) MNL model[19].

The nested multinomial logit (NMNL) model takes for granted a recursive sequential decision structure. It is sequential because a choice of an alternative at a given level of the choice hierarchy is conditional upon the outcomes of higher level choices and it is recursive because the decision also depends upon the utilities of choice options available at lower level choices (Fischer and Nijkamp, 1987, p. 10). At each level a dependence or similarity parameter θ, expresses the degree of correlation in the error terms of the alternatives. Each level transition is characterized by a variable called an 'inclusive value'. This variable summarizes the attribute values of the alternatives of lower level choices.

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function with certain properties (see Ben-Akiva and Lerman, 1985, p. 305) and with corresponding choice probabilities: $P(j|C_i) = \frac{e^{V_{ij}} G_j(e^{V_{i1}},\dots,e^{V_{iJ}})}{\mu G(e^{V_{i1}},\dots,e^{V_{iJ}})}$ whereby $G_j = \partial G(.)/\partial(e^{V_{ij}})$ is the derivative of $G(.)$ with respect to its jth argument.

[19] Another special case of GEV models is treated by Small (1987, pp. 409-424) who assumes a correlation across alternatives that are "close" when the alternatives in the choice set can be ordered a priori. This model variation is termed the "ordered logit model".

The derivation of the NMNL model from the GEV model is shown in McFadden (1978, pp. 75-96; 1984, pp. 1420-1433) and Ben-Akiva and Lerman (1985, pp. 304-310). The use of the model can best be illustrated by an example.

Suppose that we are interested in modelling an industrial location problem whereby a choice-maker i (= 1, ..., I) first chooses a region j (= 1, ..., J), to establish business and then an industrial location site k (= 1, ..., K_j), within that region. Given this choice strategy, the selection of k is subject to the selection of j, or in other words k is nested in j. The nested logit choice probability of an industrial location site k in region j, denoted as $P_i(jk)$ or $P(jk|C_i)$, is the product of the marginal probability of choosing j, denoted as $P_i(j)$ or $P(j|C_i)$, and the conditional probability of k, given that j is chosen, denoted as $P_i(k|j)$ or $P(k|j|C_i)$:

$$P_i(jk) = P_i(j)\, P_i(k|j) \qquad [28]$$

The NMNL choice probabilities are:

$$P_i(jk)=\frac{\exp(V_{ij} + V_{ik} - \theta I_{ij})}{\sum_m \exp[V_{im} + (1 - \theta)I_{im}]} \qquad [29a]$$

$$P_i(j)=\frac{\exp[V_{ij} + (1 - \theta)I_{ij})}{\sum_m \exp[V_{im} + (1 - \theta)I_{ij}]} \qquad [29b]$$

$$P_i(k|j)=\frac{\exp(V_{ik})}{\exp(I_{ij})} \qquad [29c]$$

with $I_{ij} = \ln \sum_{k=1}^{Kj} \exp(\frac{V_{ik}}{(1 - \theta)})$, and θ is a parameter to be estimated.

The similarity parameter θ also serves as a test for the proposed hierarchical decision structure. This is because θ has to fall within the unit interval $0 \leq \theta < 1$ in order that the NMNL model remains consistent with random utility maximalization. If $\theta = 0$, the NMNL model reduces to a MNL model in which region and industrial location site are chosen simultaneously and the IIA assumption holds. As $\theta \rightarrow 1$, the industrial location sites within each region are perceived to be identical (perfectly correlated) in their unobserved attributes. In that instance IIA cannot hold and the choice process must be modelled as a two-stage or hierarchical process whereby the decision-maker first chooses the region and then, conditional on the choice of region, chooses the industrial location site.

A major strength of NMNL models is their capacity to organize the decision problem hierarchically, thus simplifying the overall choice problem. However, this 'strength' is based on very strong separability assumptions that need to be imposed on the alternatives. When the hierarchical choice structure is confined to only one, the properties of the simple MNL still hold. Therefore, the NMNL models offer a convenient framework for spatial choice problems when the number of disaggregate alternatives is impractically large, and when the presence of a structure of similarities between alternatives invalidates the commonly used simple MNL model. An extensive survey of different applications of the NMNL model to problems of discrete choice can be found in e.g. Hensher (1986, pp. 657-667) and Chintagunta (1992, pp. 161-175).

Another model which circumvents the IIA-problem by assuming a sequential decision process is Tversky's (1972a, 1972b) elimination-by-aspects (EBA) model.

The EBA model describes the choice process as a covert sequential elimination process. Each alternative is characterized by a set of measurable aspects (attributes). The choice process begins with the selection of an aspect and eliminates all the alternatives that do not possess the selected aspect. This process continues until all the alternatives but one are eliminated. If a selected aspect is included in all the available alternatives, no alternative will be eliminated from the choice set and a new aspect is selected. Consequently, aspects that are common (similar) to all the alternatives under consideration do not affect the choice probability. It are the differential or distinctive aspects which play the critical role in influencing the choice probabilities. Thus, in contrast to the MNL model, the EBA model does allow for alternatives that have very different degrees of similarity. The choice process is probabilistic because no fixed prior ordering of aspects is assumed.

Tversky's EBA model is theoretically very well grounded but has not been that popular with researchers in an applied context due to some implementation problems. One such problem is that all the aspect's characteristics are essentially binary (the alternative either possesses or does not possess the aspect), so the absolute value of the characteristics play no role in the choice of the alternative. For nonbinary characteristics the choice maker refers to minimal thresholds that may cause him or her to reject or retain the alternative. However, this assumption may lead to counterintuitive results. Suppose that all the alternatives in the choice set have the same characteristics. In this case they are considered to be equiprobable. This result seems unlikely if one alternative has more of each characteristic. A second factor deals with the extend of the choice set. When there is a large number of alternatives, taking into account all possible sequences of elimination becomes a considerable time-consuming chore. As a result a number of variants exist to the EBA model such as Tversky and Sattath's (1979) hierarchical EBA model. They propose a heuristic choice procedure that avoids the complete enumeration of all the possibilities.

Apart from models that incorporate substitution effects other factors may be responsible for making the choice model context-dependent. These *context* *effects* are summarized in table 2[20].

Table 2: Context effects and their characteristics

context effects	characteristics
attraction effects	the introduction of a new alternative in the choice set increases the choice probability of an old alternative that is similar to the added alternative
choice set effects	changes in the size and composition of the choice set have an influence on the estimated parameter values
dominance effects	the introduction of an alternative that is better than all other alternatives on at least one attribute while it is not worse on the remaining attributes dominates the choice probability
edge aversion effects	individuals avoid choosing alternatives with extreme scores on a particular attribute
prominence effects	the introduction of a new alternative in the choice set causes an existing choice alternative to become more or less prominent, implying that the choice probability for this alternative may change
spatial structure effects: like (a) agglomeration effects and (b) competition effects	the spatial arrangement of the choice alternatives has an influence on the choice behaviour: like (a) when two choice alternatives, located relatively close to each other, decrease the choice probability of other alternatives and (b) when two choice alternatives, located relatively close to each other, increase the choice probability of other alternatives
threshold effects	individuals are indifferent between choice alternatives that show a small difference in utility. Therefore, only a certain threshold increase in utility may change the choice probabilities
weight shifting effects	a weight attached to a particular attribute of an alternative shifts to those attributes with the higher degrees of variability

[20] see also Smith and Yu (1982, pp. 225-249), Timmermans and Borgers (1985b, pp. 39-55; 1987, pp. 29-47), Borgers and Timmermans (1988, pp. 159-178), Eagle (1988, pp. 299-324) and Timmermans and Golledge (1990, pp. 326-328).

In conclusion, conventional discrete choice models, like the MNP and MNL model try to establish a functional relationship between the attributes of the choice alternatives and overt (observed) choice behaviour (Timmermans and Borgers, 1985b, p. 10; Timmermans and Golledge, 1990, p. 313). Due to the nature of the IIA-property a large number of context-dependent models have been developed.

2.2 Compositional multiattribute attitude models

Attitude models go as far back as 1956 when the psychologist Rosenberg (1956) first formulated his ideas on the relation between attitudinal behaviour and an individual's cognitive structure. The model tried to identify the factors that influence motivated behaviour. Most of its applications are found in the field of sociology and marketing science. Later contributions by Fishbein (1967a, 1967b) on attitudes and the prediction of behaviour, and by Cohen, Fishbein and Ahtola (1972) on the nature and uses of expectancy-value models in consumer attitude research have led to the development of the compositional multiattribute attitude model.

Compositional models have in common that the *overall utility* for a multi-attribute choice alternative can separately and explicitly be calculated. Instead of deriving the attribute values from an individual's evaluation of an alternative as a whole or through his or her selection between different alternatives the overall evaluations or attitudes are directly measured. This can only be possible if one assumes that an individual can always provide valid and accurate evaluations of the attributes independently of any specific context.

It is also assumed that the decision rule governing the choice problem is deterministic. This means that an individual chooses the alternative which according to an a priori specified combination rule yields the highest overall evaluation or most positive attitude. In most cases the combination rule is assumed linear additive, but other specifications exists. The alternative with the highest utility is then predicted as the chosen alternative and these predictions are compared with the actual choice behaviour to assess the goodness-of-fit of the model (Timmermans and Borgers, 1985b, p. 17). In a sense the compositional multiattribute attitude models are self-explanatory and do not involve a statistical estimation.

According to Timmermans (1985) the predictive ability of the compositional multiattribute attitude models is significantly less than that of decompositional models like e.g. conventional discrete choice models. But other factors also play to the disadvantage of compositional models. They do not account for context-effects, nor do they describe a realistic choice behaviour. Individuals are only asked to evaluate a certain attribute or alternative without taking into consideration the existing similarities or dissimilarities between different attributes and different alternatives. For this reason, Timmermans and Golledge (1990, p. 320) point out that only a few applications of compositional multiattribute attitude modelling exist in spatial analysis[21].

2.3 Decompositional multiattribute preference/choice models

So far choice models are assumed to be based on 'real-world' or 'revealed preference' data, that is, choices and decisions that have *actually* been made. The parameters of such a revealed choice model are estimated by relating the data on observed actual choices to a set of attributes which is assumed to influence the choice behaviour. Working with actual choices has its advantages, but it also poses some practical limitations. Aside from the high survey costs, there is always the difficulty of distinguishing the effects of hardly noticeable attributes like e.g. quality or convenience (Bates, 1988a, p. 7). As a consequence, a new choice modelling approach came to the fore known as

[21] Spatial applications of compositional multi-attribute attitude models in travel behaviour: Thomas (1976) and Knippenberg-den Brinker (1981); shopping behaviour: Timmermans (1980b); and recreational choice behaviour: Cooksey *et al.* (1982).

decompositional multiattribute preference/choice model, also termed stated preference and stated choice model.

The difference between stated preference (SP) and stated choice (SC) needs to be clarified. If the choice alternatives are ordered (ranked) or given a rating score the decision-maker expresses a preference (judgement) towards all the alternatives in the choice set. Eventually in the case of a deterministic utility-maximizing decision rule the choice alternative which is ranked first or with the highest score will be selected. The data used in this kind of approach is called 'judgement data' (Green and Srinivasan, 1978). It implies that the data is at least ordinal in measurement level. If, however, the decision-maker is asked to identify one and only one alternative out of the choice set as the 'highest' or 'best', then he or she is asked to state a direct choice instead of a mere preference. The data used in this approach is called 'choice data' (Louviere and Hensher, 1982; Louviere and Woodworth, 1983). Louviere (1988b, p. 94) points out that the differences between judgement and choice data are important because judgement data may not contain information about choice behaviour and may not satisfy various assumptions necessary to forecast choice behaviour. By definition, choice data contains information on individuals' choice behaviour, but assumptions need to be made on the several possible choice processes that underly the data.

Decompositional multiattribute preference/choice models are based on two major assumptions. First, in contrast with discrete and compositional choice models, decompositional preference/choice models are not derived from data on actual choices, but from preferences or choice for a *hypothetical* choice alternative described in terms of a set of attributes. The model therefore typically involves with choice experiments using design data. Second, unlike compositional models in which an overall utility for a multi-attribute choice alternative is obtained, decompositional models attempt to derive *part-worth utilities* (or separate attribute-level contributions of utility) which are defined on the levels of the attributes by decomposing some overall utility measure into scale values for the attribute levels. Individuals arrive at this so-called overall utility measure or value by *cognitively integrating* their evaluations on the choice alternative's attributes, thereby making subjective value judgements at the attribute levels, which combined, results in an overall judgement for the choice alternative (Timmermans, Borgers and van der Waerden, 1992, p. 408). In a sense this approach is associated with Anderson's (1974, 1981, 1982) Information Integration Theory (IIT) whereby a response is the result of the integration of information according to a certain mathematical rule (see also Lynch, 1985, pp. 1-19). Applied to choice models, this rule could be some simple combination rule or a utility function. Testing which rule will be most appropriate is an important factor within decompositional choice modelling. This measurement problem is also known as 'conjoint analysis' (Timmermans, 1984a, p. 191).

Following Timmermans (1984a, pp. 194-199) the construction of a decompositional multiattribute preference/choice model involves the following steps and decisions[22]: (i) identification and selection of the number of relevant attributes to the choice process of interest; (ii) specification of the attribute levels; (iii) selection of a suitable method for the combination of the attribute levels into profiles of hypothetical choice alternatives; (iv) choosing a suitable way to present the choice alternatives to the respondents; and (v) selection of the technique of analysis to decompose the overall preferences or choices into part-worth (or utility weights) utilities associated with the choice alternative.

A rather straightforward first step in the construction of any choice model is the identification and selection of the *number of relevant attributes*. The attributes influencing the choice behaviour can be identified on the basis of a literature

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[22] see also Timmermans and van der Heijden (1984, p. 91), Timmermans and Borgers (1985b, p. 11), van der Heijden (1986, pp. 126-139), Kroes and Sheldon (1988, pp. 14-21), Fowkes and Wardman (1988, pp. 33-38), Timmermans (1988b, pp. 18-22), Louviere and Timmermans (1990a, p. 215), Timmermans and Golledge (1990, p. 314), Timmermans, Borgers and van der Waerden (1992, p. 408).

search, focus-group or in-depth interviews, questionnaires, multidimensional scaling, rating scales, principal component analysis, correspondence analysis, factor listing, repertory grid methods, protocol analysis, etc. (see also van der Heijden, 1986, pp. 127-130). We know that individuals attach varying importance to different attributes of the choice alternative and generally base their preference or choice on a small number of relatively important attributes (Timmermans and van der Heijden, 1984, p. 91). Therefore, the omission of influential attributes or the inclusion of irrelevant attributes strongly bias the results. The attributes included must also be reasonably realistic and as dissimilar from each other as possible as they are used to differentiate between the choice alternatives. As attributes increasingly diverge from the experiences of the choice maker or from what appears plausible the responses can be expected to become less reliable. Almost similar attributes characterizing the same alternative can cause confusion and should therefore be avoided. The selection of the number of attributes is also very important. If we consider to many attributes the choice design becomes unmanageable, and, if we include to few attributes the choice alternatives show less variation. As a rule the ratio of the number of choice alternatives and the number of estimated parameters should be as large as possible.

A second step is to describe the attributes in terms of *attribute levels*. Attribute levels make it possible to further specify the attribute. In most cases the number of levels is confined to just two or three, however, more levels are possible. An attribute defined in terms of two attribute levels usually takes on the particular form of 'yes' or 'no', 'present' or 'absent', 'small' or 'large', 'good' or 'bad', 'low' or 'high' etc. As in the case with the number of attributes, an increase in attribute levels makes the choice design more complex. This problem is viewed as an important practical limitation in the application of decompositional models. A possible solution has been put forward by Louviere (1984, pp. 148-155) and Louviere and Timmermans (1990b, pp. 291-309; 1990c, pp. 127-145). The method is called 'hierarchical information integration' and can be considered as an extension of Anderson's IIT. The method is based on the assumption that a decision maker divides the set of attributes that influence his or her choice behaviour into subsets, thus hierarchically structuring the choice problem. The subsets are then separately evaluated and aggregated to arrive at an overall preference or choice (Borgers and Timmermans, 1993, p. 49).

A third decision concerns the selection of the *method for combination* of the attribute levels into profiles of hypothetical choice alternatives. The choice profiles can be generated using (i) a full factorial design, (ii) a fractional factorial design, or (iii) a trade-off design.

A full factorial design generates all possible combinations of attribute levels and allows one to estimate all main and all interaction effects. This approach can only be used if the number of attributes and attribute levels is limited because the respondents can only evaluate a fairly small number of alternatives (only 9 to 16 according to Kroes and Sheldon, 1988, p. 14) at a time[23]. When a full factorial design yields too many profiles the number can be reduced by adopting a fractional factorial design. In that case only a selection or fraction of all possible combinations is presented to the respondents. It is assumed that certain interaction effects are negligible and can be ignored. The simplest fractional factorial design allows only the estimation of all main effects[24]. It needs to be stressed that when factorial designs, full or fractional, are used, there is a chance that the attribute levels are combined in profiles that seem unrealistic or infeasible to the respondent. This problem can be solved by enabling the respondents to comment on what appears to them somewhat implausible situations and amend the choice design accordingly. A third

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[23] A full factorial design for four attributes with two levels would generate 2^4 = 16 profiles. But ten attributes all defined in terms of three attribute levels would yield 3^{10} = 59049 experimental treatments ! Clearly, such a choice design is unmanageable.

[24] The simplest fractional factorial design (also called orthogonal design) of the 2^4-design yields 6 = (2*4-2) main effects. In the case of the 3^{10}-design 27 = (3*10-3) profiles, all main effects, are generated.

approach is called the trade-off design (see e.g. Johnston, 1974). It differs from the two above mentioned in that the respondents are asked to consider the attributes in pairs. This limits the number of possible hypothetical choice alternatives. But the pairwise comparison assumes that the trade-offs take place independent of the attributes not under consideration. Thus, interaction effects yield inaccurate results. Furthermore, as noticed by Timmermans (1984a, p. 196), the way of presenting the attribute combinations may also have an influence on the comparison. As a result, alternative designs (e.g. balanced design) have been put forward to construct choice profiles (see Green, 1974).

A fourth step in the construction of a SP or SC model is the decision upon the *survey method*. It involves choosing a suitable way to present the choice profiles to the respondents. Kroes and Sheldon (1988, p. 16) have a strong preference for face-to-face interviews because they allow for flexibility. Timmermans (1984a, p. 197) mentions a pictorial representation by way of index or option cards. Mail-back surveys (questionnaires) can be used for SP or SC research provided the task for the respondents is fairly easy and well explained. Mailing could be combined with a telephone follow-up. A more recent development, pointed out by Bradley (1988, pp. 131-136), is the use of portable computers to undertake computer-assisted interviews.

The fifth and final step deals with the selection of the *technique of analysis* to decompose the overall preferences or choices as provided by the respondents into part-worth utilities associated with the hypothetical choice alternatives. The method used, is called 'conjoint analysis'. In two excellent reviews Louviere (1988a, 1988b) distinguishes between three main conjoint paradigms: (i) rank-order conjoint methods, also called 'axiomatic conjoint measurement', (ii) rating-scale conjoint methods, also known as 'functional measurement', and (iii) discrete data conjoint methods. The first two relate to stated preference, the third to stated choice models.

Rank-order conjoint methods rely on a real ranking of the choice alternatives by the respondents. Through the use of certain computer algorithms estimations of the part-worth utilities can be derived. Most commonly, the iterative optimisation technique MONANOVA (acronym for MONotonic ANalysis Of VAriance) is used. It estimates the attribute part-worths by least-squares procedures in such a way that the fit between observed and predicted rankings is optimized, assuming that the utility specification is additive. A badness-of-fit index (called 'stress' value) indicates the adequacy of the proposed estimation. Rank-order methods have the advantage that the respondents do not have to rate the sets of attribute combinations. In that light Green and Srinivasan (1978, p. 112) argue that ranking is less difficult than rating. But Louviere (1988b, p. 95) points out that most individuals are not perfectly consistent in their ranking, implying that there is error in their data. Louviere (1988a, p. 25) also mentions that rank-order conjoint methods lack a formal theory and an error theory on which to base statistical tests of the part-worth parameters. And, Louviere (1988a, p. 26) continues, that researchers should be most cautious about using stress measures to determine the adequacy of the model's fit to the data.

Rating-scale conjoint methods differ from ranking procedures in that the respondents are asked to express their degree of preference for the various choice alternatives through the use of a score or rating scale. Timmermans (1984a, p. 198) and Hensher *et al.* (1988, p. 55) advice that the respondents should first select the most preferred alternative, giving it the highest score, and then provide ratings for the remaining choice alternatives as compared to the rating of the most preferred. Unlike rank-order methods, the rating-scale conjoint methods are based on a theory. This is called the Information Integration Theory (IIT) which was developed by Anderson (1974, 1981, 1982). It is a theory about the behaviour of numerical data in response to multiple pieces of information. It assumes that the overall evaluation of the choice alternatives is inferred by the respondent's combination or integration of all available information about the different determinant attributes. New information can change the set of determinant attributes and the respondent's beliefs about the attribute values can change as well by additional information prior to the choice. Following the evaluation, the respondents form final choice sets and decide which alternative, if any, to choose. The IIT has the advantage of possessing a theory of errors which permits it to falsify the model, something which was not possible using the ranking method. Let us know focus on how the theory is implemented and applied to spatial choice problems (see also Louviere, 1988a, pp. 13-15). The resemblance with random utility theory will soon become clear.

For a choice maker i (= 1, ..., I), X_{ijk} represents a physical measure for an alternative j (= 1, ..., J) characterized in terms of a number of physical variables or a set of determinant attributes k (= 1, ..., K). This physical measure is subject to the choice maker's own beliefs or impressions about the different attributes, resulting in a 'belief measure', denoted S_{ijk}. Beliefs or impressions about an attribute do not have to correspond with the physical characteristics. The functions $f1_k$ describe the relation between the physical and belief measure as follows:

$$S_{ijk} = f1_k\ (X_{ijk}) \qquad [30]$$

The k-th part-worth utility associated with the k-th attribute of alternative j is defined as $V(S_{ijk})$. It represents the choice maker's opinion or feelings regarding the unknown part-worths for the levels of the alternative's attributes. The relation between S_{ijk} and $V(S_{ijk})$ is given by the functions $f2_k$:

$$V(S_{ijk}) = f2_k\ (S_{ijk}) \qquad [31]$$

The overall utility value for an alternative j, U_{ij}, can be written as a function of the part-worth utilities:

$$U_{ij} = f3\ [V(S_{ijk})] \qquad [32]$$

The probability that an alternative j is chosen from a choice set C_i is denoted as:

$$P(j \mid C_i) = f4\ (U_{ij}) \qquad [33]$$

By elementary substitution, we derive:

$$P(j \mid C_i) = f4\ \{f3\ [f2_k\ (f1_k\ (X_{ijk}))]\},\ \text{or,} \qquad [34a]$$

$$P(j \mid C_i) = F\ (X_{ijk}) \qquad [34b]$$

where F is a composite function of the indicated functions in equation [34a]. This composite function indicates that several different levels of explanation of choice behaviour are possible: (i) explanations based entirely on physical variables, (ii) explanations based only on belief variables, (iii) explanations using only the part-worths, and/or (iv) explanations containing combinations of these variables (Louviere, 1988a, p. 14).

According to the IIT the overall utility of an alternative is linearly related to the choice maker's response on a category-rating scale. That is:

$$U_{ij} = a + b\ R_{ij} + e_{ij} \qquad [35]$$

where R_{ij} is the observed response on a category-rating scale, e_{ij} is a normally distributed error term, and a and b are parameters.

The aim of the model is to estimate the part-worth utilities in such a way that, given $f3$ is an additive function, the choice maker's rating of the alternatives is as closely as possible resembled by the physical and belief variables characterizing that alternative. If we combine the functions $f1_k$ and $f2_k$ from equations [30] and [31] we are able to relate the unknown part-worth utilities to the determinant attributes. This results in: $V(X_{ijk}) = f3_k\ (X_{ijk})$. Note that the choice maker's beliefs are now captured in the functions $f3_k$. Assuming that these functions have a linear relationship, indicated by a parameter β_k, than $V(X_{ijk}) = \beta_k X_{ijk}$. This enables us to relate R_{ij} to X_{ijk} as follows:

$$R_{ij} = \sum_k \beta_k X_{ijk} + e_{ij} \qquad [36]$$

Through the use of e.g. regression analysis estimates for the β_k's can be found, thus deriving a weight for the part-worth utility of the *k*-th attribute from the choice maker's preference via the rating-scale method.

Discrete data conjoint methods rely upon an experimental design which satisfies the statistical requirements of MNL choice models. Unlike the ranking-order or rating-scale methods, this method does not require any assumptions to be made about order or cardinality of measurement. It has the advantage that one can estimate choice models directly from the choice data, assuming that the response data are discrete. The basic idea is that choice makers in real live situations probably do not rank nor rate alternatives, but they simply select one alternative or they choose not to select at all. In the choice experiments the choice maker is shown different sets of alternatives and is asked to choose among them or to allocate resources to them. This way of working allows one to study how choices vary if size or composition of choice sets are altered (Louviere, 1988b, p. 100; Hensher *et al.*, 1988, pp. 55-56). A drawback to this method is that the choice experiments are more difficult to design because one needs to develop two separate designs: one to create choice alternatives and a second to place the choice alternatives into choice sets.

Finally, Timmermans (1984a, pp. 198-199) proposes still other methods to measure the preference for the selected hypothetical choice alternatives. These include (graded) pair comparisons, magnitude scales, dollar-metric approach and constant-sum method.

In the area of spatial analysis examples of applications of the decompositional multiattribute preference/choice models can be found with respect to (i) travel behaviour[25], (ii) migration and residential preferences and choice[26], (iii) shopping behaviour and retailing[27], (iv) recreational behaviour[28], and (iv) preferences or choice of industrial or office (re)location site[29].

To conclude this paragraph let us make a comparison of the two most commonly used static modelling approaches in spatial analysis: conventional discrete choice modelling (revealed choice) and decompositional multiattribute

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[25] see e.g. Davidson (1973), Norman and Louviere (1974), Levin (1975, 1977), Louviere (1976, 1981), Louviere and Norman (1977), Norman (1977), Lerman and Louviere (1978), Hensher and Louviere (1979, 1983), Louviere *et al.* (1980), Timmermans and Overduin (1980), Louviere and Hensher (1982), Shelden and Steer (1982), Louviere and Kocur (1983), Bates (1983, 1988c), Bradley and Bovy (1984), Royal Aeronautical Society (1986), Timmermans (1987a, 1987b, 1988a), Wardman (1986), Fowkes and Wardman (1988), Hensher, Barnard and Truong (1988), Dinwoodie (1989), Bovy and Stern (1990), Anderson *et al.* (1992) and Ettema (1993).

[26] see e.g. Fielder (1972), Knight and Menchik (1976), Louviere and Meyer (1976), Louviere and Henley (1977), Lieber (1978, 1979), Louviere (1978, 1986, 1988c), Veldhuisen (1979), Veldhuisen and Timmermans (1981, 1984), Phipps and Carter (1984, 1985), Phipps and Clark (1988), Phipps (1989), Timmermans (1989), Louviere and Timmermans (1990c), Timmermans *et al.* (1992) and Borgers and Timmermans (1993).

[27] see e.g. Louviere and Wilson (1978), Schuler and Prosperi (1978), Schuler (1979), Timmermans (1980a, 1982, 1983), Louviere and Meyer (1981), Recker and Schuler (1981), Burnett and Hanson (1982), Hendriks (1983a, 1983b), Timmermans, van der Heijden and Westerveld (1983, 1984a, 1984b), Timmermans and van der Heijden (1984), Timmermans, van der Heijden and Borgers (1984), Louviere and Gaeth (1986), van der Heijden (1986), Bates (1988c), van der Heijden and Timmermans (1988a) and Timmermans, Borgers and van der Waerden (1992).

[28] see e.g. Louviere (1974), Stutz and Butts (1976), Allton (1981), Curry *et al.* (1983), Louviere and Hensher (1983), Hensher and Louviere (1984), Lieber and Fesenmaier (1984), Louviere and Woodworth (1985), Timmermans (1987c), Lieber, Fesenmaier and Bristow (1988), van der Heijden and Timmermans (1988b), Haider and Ewing (1990), Louviere and Timmermans (1990b, 1992) and Batsell and Louviere (1991).

[29] see e.g. Timmermans (1986), van Dinteren and Reitsma (1986) and Moore (1988, 1990).

preference/choice modelling (stated preference/choice). Both approaches have a number of advantages as well as a number of disadvantages as put forward by e.g. Timmermans (1984a, pp. 214-216; 1984c, pp. 99-100), van der Heijden (1986, pp. 149-152), Kroes and Sheldon (1985, pp. 205-206; 1988, pp. 12-13), Wardman (1988, p. 89), Louviere and Timmermans (1990a, p. 214) and Timmermans, Borgers and van der Waerden (1992, pp. 414-415). Looking at the RC models, it may be argued that the collection of the data is somewhat easier than for SC models. But the latter is less expensive because the sample sizes are smaller. In the RC model the parameters are context-dependent. They are influenced by personal, societal and spatial constraints. The spatial structure of the study area also bias the results. Statistically, problems such as multicollinearity among the explanatory variables of interest, the difficulty of having sufficient variation in the data and IIA assumption may occur and can put some restrictions on the RC variables. The RC method can also not be used to evaluate a condition which does not yet exist. On the other hand, in the SC approach the parameters are estimated context-free which in turn produces somewhat more accurate predictions. The method is also easier to control and has a greater flexibility in dealing with a wider variety of variables. However, it also requires specialized advance knowledge to construct a good experimental design. The most important drawback of all SC models, as noticed by a number of authors, is the assumption that decision-making in an experimental setting equals real world choice behaviour. There is a risk that people may not necessarily do what they may say in which case the stated choice may not correspond closely to their actual preferences. In sum, both methods, RC and SC, should be used in a complementary way depending on the type of spatial choice analysis. Another possible solution is a combination of both methods. This is tried in our last paragraph on static choice models which deals with the hybrid choice models.

2.4 Hybrid evaluation models

Hybrid models differ from compositional and decompositional models what the measurement procedures of the evaluation of choice alternatives and attribute levels is concerned, and with respect to the estimation of the importance weights. In a compositional (self-explicated) model an individual's evaluation of the attribute levels can separately and explicitly be measured. The choice alternative's overall evaluation is then computed or calculated from those attribute levels taking into account a number of different (measurable) subjective importance weights. In a decompositional model the overall evaluation associated with a set of choice alternatives is measured rather than computed. The part-worth utilities associated with the attribute levels are derived (decomposed) from this measurement. In hybrid evaluation modelling the decision maker makes an overall evaluation of each choice alternative *and* an evaluation of the different attribute levels characterizing the choice alternative. On the basis of those two evaluations an estimate using regression analysis can be found for the importance weights. This makes that the importance weights are not measured but estimated using multiple regression. Variations in the estimation method result in different hybrid model constructions. Hybrid choice models sometimes involve both discrete (qualitative) and continuous (quantitative) variables.

Timmermans and Borgers (1985b, pp. 18-22), Timmermans (1987c, pp. 67-76) and Timmermans and Golledge (1990, pp. 320-322) distinguish at least three types of hybrid models and area of applications: (i) models most commonly used in behavioural science and management science, (ii) models used in marketing, and (iii) models applied in marketing science. Only the first is most closely related to spatial choice analysis and theorized in the work of Huber (see Huber, Sahney and Ford, 1969; Huber, Daneshgar and Ford, 1971; Huber, 1974). With respect to spatial applications of the hybrid model the number of studies is very restricted. Miller and Lerman (1981) conducted a study of the retail store location of the clothing business. In their model clothing retailers decide in which shopping center to set up store and also the square feet of floor space they should rent and the number of employees they should hire to function optimally at that location. Timmermans (1987c) carried out a hybrid study in the field of outdoor recreation behaviour. He paid particular attention to the predictive ability of hybrid models and found that hybrid models tended to preform better than compositional models but less that decompositional models.

The models so far reviewed all have in common that they deal with static choice behaviour. In recent years rapid developments are made in the field of dynamic choice behaviour.

3 Dynamic choice models

Dynamic discrete choice models explicitly take into account choice behaviour over *time*. The effects of past experience on choice behaviour are incorporated in the model. This makes it possible that preferences or choices may change as the decision maker adapts his or her behaviour to new situations.

The intertemporal nature of the choice problem has its implications on the collection of the data. It is no longer sufficient to use cross-sectorial data, but longitudinal survey data are needed. In most cases a classical panel survey is used whereby a same group of decision makers is asked to choose between different alternatives at different points in time. The great potential of panel data is that it enables one to explicitly recognize the intertemporal nature of the choice outcomes, especially the effects of experience on decisions (Fischer and Nijkamp, 1987, p. 15). A drawback of the method is that the original panel may become unrepresentative as panel members could drop out during the experiment due to the process of 'panel attrition' (Wrigley, 1986, p. 86). To circumvent this problem Wrigley (1986, pp. 85-87) proposes three other possible longitudinal survey methods. These include (i) repeated cross-sectorial surveys, (ii) rotating panel surveys, and (iii) split or mixed panel surveys.

Apart from specific data requirements the extension from static to dynamic choice models raises two fundamental methodological issues (Heckman, 1981a, p. 115; Halperin and Gale, 1984, p. 11; Halperin, 1985, p. 570): (i) how to take *structural state dependence effects* into account, and (ii) how to deal with *serial correlation or spurious state dependence* ?

Structural state dependence (or 'feedback' as it is sometimes termed) refers to the dependence of current on past behaviour and of future on current choice behaviour. Wrigley (1986, pp. 94-95) indicates several sources of state dependence influencing the choice outcome. He mentions first-order or higher order Markov effects (choice outcome depends on previous choices), duration effects (choice outcome depends on the length of time that elapsed since the last choice), lagged duration effects (choice outcome is influenced by previous elapsed interchoice time) and occurrence effects (choice outcomes depends on the number of times the various choice outcomes have been selected within a specific time period back from the present). Serial correlation or spurious state dependence is the result of omitting variables in the choice problem. Because of omitted variables we may draw incorrect inferences concerning the effect of the observed exogenous variables on the choice probabilities even though the omitted and observed variables may not be correlated.

One of the first attempts to introduce both structural and spurious state dependence effects to conventional discrete choice models was made by Tardiff (1980). He views a recurrent choice as a sequence of static utility maximizing choices by the decision makers whose utility function may have been influenced by certain individual, structural and spurious state dependence effects. Tardiff (1980, pp. 25-30) suggests that the decision maker's standard utility function for random utility models, as originally specified in equation [5], should be replaced by:

$$U_{ijt} = \beta_{kt} X_{ijkt} + \sum_{m} \gamma_{jm} C_{im(t-1)} + \tilde{\epsilon}_{ij} + \epsilon^{*}_{ijt} \qquad [37]$$

whereby U_{ijt} represents the utility of choice alternative j for a choice maker i at time t; $\beta_{kt} X_{ijkt} = V_{ijkt}$ represents the deterministic utility of an alternative j for a choice maker *i* written as a linear additive function of various observable attributes *k* at time *t*; $C_{im(t-1)}$ is a variable which equals 1 if choice maker *i* chooses *m* in the previous period *t-1*, and 0 otherwise; $\bar{\epsilon}_{ij}$ is an error term that allows for unobserved time-invariant effects; ϵ_{ijt}^{*} is an error term that varies among decision makers and time periods; and *t* (= 1, ..., T) is an exogenously given sequence of time periods.

The parameter γ_{jm} needs to be estimated. If its value is positive (negative) it indicates an increased (decreased) choice probability in the subsequent period. By putting various components of the above specified utility function equal to zero, different special cases of the general data discrete choice model may be distinguished (see e.g. Fischer and Nijkamp, 1987, p. 18).

A second pioneer on dynamic discrete choice models is Heckman (1978, 1981a, 1981b). He developed a series of models for investigating the effects of conditional probability relationships between the occurrence of an event in one period and its occurrence in previous periods. In contrast with Tardiff's (1980) dynamic discrete choice model Heckman's (1981a) general model of dynamic choice can be used to analyze the structure of discrete choices made over time from a direct consideration of a complex error variable structure. This approach is called 'random-effect modelling' (Heckman, 1981a, p. 127). "The proposed model is sufficiently flexible to take into account time dependent explanatory variables, general spurious state dependence patterns for unmeasured attributes and complex structural state dependence inter-relationships among decisions taken in different time periods" (Fischer and Nijkamp, 1987, p. 19).

For the sake of illustration the Heckman (1981a, pp. 121-122) model is derived as follows[30]: first, from a random sample of *I* choice makers, information is

[30] see also Halperin (1984, pp. 11-12), Halperin and Gale (1985, pp. 571-572), Timmermans and Borgers (1985, p. 101; 1989, p. 16) and Fischer and Nijkamp (1987, p. 19).

assembled on the presence or absence of an event (that is, a discrete choice) in each of T equi-spaced time intervals. It is assumed that an event in period t for a choice maker i can occur if and only if a continuous latent random variable, $Y(i,t)$ crosses a threshold. Only for simplicity and convenience this threshold is assumed to be zero. If the event occurs, the dummy variable $d(i,t) = 1$ if and only if $Y(i,t) \geq 0$; controversy, $d(i,t) = 0$ if the event does not occur. The random variable $Y(i,t)$ may be decomposed into a purely random disturbance component $\epsilon(i,t)$ and a deterministic component, $V(i,t)$ which gives the following:

$$Y(i,t) = V(i,t) + \epsilon(i,t) \qquad [38]$$

with $Y(i,t) \geq 0$ if and only if $d(i,t) = 1$, and, [39a]
$Y(i,t) < 0$ if and only if $d(i,t) = 0$. [39b]

The distribution of $d(i,t)$ is generated by the distribution of $\epsilon(i,t)$ and $V(i,t)$. In principal the distribution of the purely random error term may take on various specifications, but Heckman assumes that the disturbances are jointly normally distributed [$\epsilon(i,t) \sim N(0,\Sigma)$] similar to the MNP model.

If $Y(i,t)$ is assumed to be a linear functions of exogenous variables, $X(i,t)$, lagged values of $Y(i,t)$, and past outcomes $d(i,t')$, $t' < t$, Heckman's general model of dynamic choice may be expressed as follows:

$$Y(i,t) = \beta_k X(i,t) + \sum_{j=1}^{\infty} \gamma(t-j,t)\; d(i,t-j) + \sum_{j=1}^{\infty} \lambda(j,t-j) \prod_{l=1}^{j} d(i,t-l)$$

$$+ G(L)\; Y(i,t) + \epsilon(i,t) \qquad [40]$$

with $G(L)$ is a general lag operator of order K, [$G(L) = g_1L + g_2L^2 + \ldots + g_KL^K$, $L^K\; Y(i,t) = Y(i,t-K)$] and β_K, γ, and λ are coefficients. The five terms on the right hand side of equation [40] all relate to different effects. These are (i) the effects of the observed choice-relevant attributes on utilities at time *t*, *X*(*i*,*t*); (ii) the effect of the entire past history on choice behaviour at time *t* represented by the lagged values of *Y*(*i*,*t*); (iii) the cumulative effect on current choices of the most recent continuous experience in a state (that is, a discrete choice); (iv) the effect of previous relative evaluations of the two states on current choices (habit persistence); and (v) random effects.

By imposing various restrictions on the coefficients and the distribution of the error term, a number of special cases may be derived from the general model. Without pursuing the subject any further, we mention such models as Bernoulli models, Markov models, renewal processes and Pólya schemes (see Heckman, 1981a).

Apart from Tardiff (1980) and Heckman (1981) similar approaches to dynamic discrete choice modelling have been suggested by other researchers. The dynamic extensions of the multinomial probit model were theorized by Daganzo and Sheffi (1982) and applied by e.g. Johnson and Hensher (1982) and Avery *et al.* (1983). Daganzo and Sheffi (1982, pp. 1377-1388) showed that the choice of a structural state dependence model, a serial correlation model, or any combination of the two is simply a model specification issue that can be decided by the researchers. The use of MNP allows for the investigation of a wide range of problems, particularly those associated with heterogeneity and state dependence. The major drawback to the model, in fact to any MNP model, is that the computational complexity of the estimation process increases with the product of the number of alternatives and time periods which can be handled. Therefore, most of the MNP research is confined to the binary case. Dynamic extensions of the logit model which account for the effect of the time factor and interactions between individuals first appeared in the work of Krishnan and Beckmann (1979) and, more important, de Palma and Lefevre (1983). Krishnan and Beckmann (1979, pp. 218-231) developed a dynamic binary logit model. Their choice model incorporates threshold effects and is able to capture individual preference indifferences. The model proposed by de Palma and Lefevre (1983, pp. 103-124) is a multinomial logit choice model in which decision makers are able to interact in their decision process. As a consequence, the attributes describing the decision maker's choice process also depend on the behaviour of other choice makers. The model is formulated as an interactive continuous-time Markov process. In trying to evaluate the dynamic logit model Sonis (1984, p. 29) writes the following: "Just as the static multinomial logit model is characterized by its simplicity, its attractive analytical properties, and its interpretability, the incorporation into the logit model of time and social interaction transforms it into a mathematical intractable dynamic model."

In the last few years the field of dynamic choice modelling is rapidly growing. Fischer and Nijkamp (1987, pp. 21-23) advance a number of complementary and alternative approaches to dynamic choice modelling. First, in the *human activity constraint time budget approach* spatial choice decisions are viewed within a broader context and one uses a more realistic and more complex conceptualization. For instance, in this approach much attention is paid to the effect of multipurpose and multistop trips on business location and human shopping behaviour (see Hanson, 1980). The method looks appealing but the approach is essentially descriptive rather than explanatory and predictive. Second, in the so-called *heuristic choice modelling approach* one explicitly attempts to replicate individual decision making processes. With the help of computational process models choice making behaviour is simulated. Such models are important in the case of complex choice problems in which exhaustive research is infeasible. A third development in dynamic modelling is the *master-equation approach*. The method originates from sociology and tries to link micro and macro levels of a system (see Weidlich and Haag, 1983). It can take into account synergetic effects in the behaviour of different individuals (learning effect, social adaption processes, etc.) and allows to include micro utility elements in the choice probability distribution.

4 Concluding remarks

The primary aim of this paper was to review the fundamental principles of discrete choice modelling in the context of spatial choice behaviour. In particular, two general approaches of modelling were distinguished: static and dynamic discrete choice models.

Static choice models are theoretically very well grounded and have been very popular with researchers in an applied spatial context. The most well-known static discrete choice model is the multinomial logit (MNL) model. It offers a computational advantage that is unmatched by any other static model and, therefore, has widely been applied in a number of spatial choice studies. However, the MNL model suffers from the "independence from irrelevant alternatives" (IIA) axiom. This states that the choice probability of two seemingly similar alternatives is independent from one another. To circumvent this problem researchers have developed a number of non-IIA choice models such as the general extreme value model, the nested MNL model and the elimination-by-aspects model. At the same time a new modelling approach came to the fore, called decompositional multiattribute preference/choice model. This approach differs from conventional discrete choice models in that the preferences or choice are derived from hypothetical instead of actual choice alternatives. The method offers the advantage of making context-free estimates of the model's parameters which in turn produces somewhat more accurate predictions.

Dynamic discrete choice models take account of the time factor in the choice analysis. Most dynamic extensions of static discrete choice models evolve around the problem of how to deal with structural and spurious state dependence ? A wide variety of dynamic models exists, but the number of applications is rather restricted. This is due to the fact that data collection is not easy (longitudinal survey data are required) and the model's statistical complexity can pose some problems (feedback elements, heterogeneity and non-stationarity). Dynamic models are especially useful in cases of recurrent discrete choice situations such as short-run destination choices like shopping travel.

Discrete choice models are but one possible tool to analyze spatial choice behaviour. Other techniques of analysis exists upon which we have not commented. To name but a few, gravity and entropy-maximizing models (see e.g. Wilson, 1970 and 1974; Ewing, 1974; Webber, 1975; Cesario, 1976) try to explain spatial interactions and patterns resulting from aggregate individual choices across regions. Spatial variety seeking models (see e.g. McAlister, 1982; Borgers, van der Heijden and Timmermans, 1989) aim at predicting spatial choice-pattern on the basis of transition probabilities (the chance of choosing another alternative on the next choice-occasion). Stochastic models of buying behaviour such as brand/store choice models and purchase incidence models (see e.g. Timmermans and Borgers, 1989; Timmermans and Golledge, 1990) to study spatial consumer choice behaviour like the selection of stores or shopping centres. Decision net approaches (see e.g. Bettman, 1979; Park *et al.*, 1981; Timmermans and van der Heijden, 1987) try to uncover individual choice and decision making processes by way of a net or tree structure.

It soon becomes clear that spatial choice behaviour and the problem of human decision making well exceeds the boundaries of regional geography. The relation with marketing, sociology, economics, planning, architecture, psychology, urban design, traffic engineering, and so on, make it possible that theories, models and applications on spatial choice behaviour are constantly growing and expanding.

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