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RELATION OF THE NBER MODEL TO EXISTING MODELS

THE NBER URBAN SIMULATION MODEL is perhaps best conceived of as a hybrid of the empirically based computer simulation models that have been used during the past ten years in land-use transportation studies and the economic theories of location and urban spatial structure that have been developed by urban economists during roughly the same period.[1] Both kinds of models have improved our understanding of the processes of urban development, but both are seriously deficient in a number of important respects. One reason is that there has been relatively little cross fertilization between these two model-building traditions.

Engineers and planners, the principal architects of most previous urban simulation models, have based their models on empirical regularities obtained by analyzing the results of large-scale surveys, and have given little or no consideration to the theoretical problems emphasized in economic theories of location and urban structure.[2] In the same way urban economists have paid scant attention to the descriptions of empirical reality constructed by model builders for urban transportation studies.

An important exception is the model developed, a decade ago, by John Herbert and Benjamin Stevens.[3] They proposed the use of a linear programming algorithm as the core of a residential location

1. A survey and critique of the land-use models developed for six of these studies is presented in Brown et al., *Empirical Models*, especially chaps. 2-8.

2. For an excellent discussion of how several of these models relate to an economic theory of the market for urban land see Lowry, "Seven Models of Urban Development."

3. Herbert and Stevens, "Model for Residential Activity," pp. 21-36.

model for the Penn-Jersey Transportation Study. They conceived of their linear programming model as a direct analog to the utility maximizing behavior assumed in economic theories of location and urban structure. Although work has continued on this model since its conception, problems of both estimation and theory have prevented its implementation.[4]

The NBER Urban Simulation Model has close familial ties with the economic theories of location and urban spatial structure developed by urban economists during the past decade. It differs from these theories principally in terms of the greater realism of its assumptions and its far more detailed representation of urban structure. For these characteristics it owes much to the urban simulation models developed by transportation planners.

Economic Theories of Location and Urban Spatial Structure

All economic models of residential location and urban spatial structure depict the locational decisions of urban households as resulting from utility-maximizing behavior.[5] Specifically, in these models it is assumed that a household chooses that residential location which maximizes its real income. This behavioral assumption plus the assumptions that all employment is located at the center and that monthly travel outlays increase as the distance between work and home increases permit the authors of these theories to generalize about the locational patterns of different income groups and the spatial configuration of housing prices and density. Although in these theories less attention is paid to the determinants of industry location, firms are depicted as choosing that location within the metropolitan region that maximizes their profits.

Within the several models the precise formulation of the problem differs. However, in every case competition for sites more accessible

4. Britton Harris has been responsible for much of the further development of this model. See his papers, *Linear Programming and Land Uses* and "Basic Assumptions."

5. Alonso, *Location and Land Use;* Kain, "Journey-to-Work"; Mills, "Aggregative Model"; Muth, *Cities and Housing;* Wingo, *Transportation and Urban Land.*

to the center produces a systematic decline in the price of urban land as distance from the core increases. These rent gradients and the greater travel costs required to reach more distant residential locations interact to influence both the location of particular households and the intensity of residential development. In the typical theoretical treatment, heads of households that require larger amounts of urban land find it advantageous to commute long distances from the single employment center to outlying residences. Heads of households that require smaller amounts of land or have unusually high transportation costs find that the savings from commuting are too small to justify the long trips necessary if they were to reside on cheaper peripheral land. As a result, they reside at central locations. Because land is expensive in central locations, it is used more intensively, and densities decline with distance from the center.

Although the theories yield nearly identical conclusions about the locational patterns of income groups and the density of development with distance from the center, a variety of analytical tools are employed in reaching these conclusions. For example, Alonso obtains this result by postulating that a household maximizes its real income while choosing between three goods: employment accessibility (the location of the housing), residential space (the quantity of residential land used by the household), and a composite good representing all competing goods and services.[6] Since the price of residential space declines with distance from the center, the cost of residential space to the household decreases with distance from the center and with reductions in quantity. Thus, the magnitude of the saving from commuting a given distance is larger the greater the amount of residential space consumed. In contrast, the household's accessibility costs (the time and money spent commuting) depend only on the distance it lives from the center. The household's utility-maximizing location then depends on the trade-off between the saving in housing costs obtained by residing on land further from the center and the resulting increased commuting costs. The optimal distance for a given household depends on how much residential space it consumes.

6. Alonso, *Location and Land Use.*

The greater its consumption of residential space, the further it will locate from the center. Alonso explains the tendency for higher-income households to reside in suburban areas by the tendency for residential space consumption to increase with income.

Muth and Mills employ somewhat different methods to obtain these same results.[7] They assume that households choose between only two goods: housing and a composite good representing all other competing goods and services. The homogeneous good, housing, can be produced using different quantities of land and nonland factors of production. Thus, in central areas where land is relatively expensive housing producers use relatively less land and densities are higher than in areas more distant from the center. The price of housing also declines with distance from the center. As a result households that consume relatively large quantities of housing find it advantageous to commute to areas further from the center. Since the consumption of housing increases with income, high-income households live further from the center than low-income households.

These models have widespread acceptance, and many persons believe that they satisfactorily explain the geographic stratification of different income groups and the level and slope of density gradients at any moment in time, as well as changes in these distributions over time. For example, in these models, the tendency for low-income households to locate in the central parts of cities is attributed to the small quantity of housing they consume. The existence of slums is explained as the natural result of market forces and the low maintenance expenditures made by centrally employed low-income households. Historical declines in the density of urban areas are alleged to be the result of secular increases in incomes and declines in the cost of passenger transportation.

These models contain useful insights into the determinants of residential location and the behavior of urban housing markets, and there is undoubtedly a good deal of truth in the conclusions the model builders obtain about the determinants of central-city declines in population, the suburbanization of urban households, and the creation of slums. However, closer examination of these models,

7. Muth, *Cities and Housing:* Mills, "Aggregative Model."

and especially a comparison between the assumptions on which they are based and reality, raises serious doubts about their completeness.

Any theory must abstract from and simplify reality in order to make the world understandable. Indeed, this is the essence of good theory. However, the admission that simplifying assumptions are both desirable and necessary does not mean that the realism of a model's assumptions should be ignored. Existing economic theories of location and urban structure employ a number of questionable assumptions. As a result, their conclusions may be incorrect or misleading.

An appropriate test of an economic theory of location and urban spatial structure is its ability to explain historical patterns of urban development. There have been a number of ingenious attempts to test these theories empirically, and many persons believe these tests substantiate the theories.[8] Unfortunately, the tests, generally based on aggregate data, have little power and do not provide satisfactory measures of the extent of correspondence between theory and reality. As a result it is important to examine the realism of the model's assumptions and to consider the implications of alternative assumptions. Existing economic theories of location and urban spatial structure seem particularly vulnerable on three counts:

1. They assume that all production takes place at a single location.
2. They obtain only long-run equilibrium solutions. As a result capital stocks are entirely ignored as are the effects of heterogeneous, durable, and locationally fixed capital.
3. They contain no acknowledgment of the various interdependencies that appear to be important in urban housing markets. These include housing consumption and production externalities, racial segregation and discrimination, and the provision of local public goods.

The Detroit Prototype deals explicitly with the first two problems. More advanced versions of the NBER model will deal with the third set of issues. As a consequence, it is useful to view the NBER Urban Simulation Model as an economic theory of residential location

8. The most elaborate tests are by Muth, *Cities and Housing*. Other evidence is contained in Mills, "Urban Density Functions."

and urban spatial structure which includes a large number of spatially separate workplaces and which explicitly incorporates durable and heterogeneous stocks of residential capital.

The Monocentric Assumption

The authors of existing economic theories of residential location and urban spatial structure assume that all production takes place at a single center. They acknowledge the lack of realism of this assumption, and all attempt to incorporate some noncentral employment into their models. Typically, they define a category of local workers who provide services to the neighborhood. The inclusion of these local workers into the model cannot be regarded as a meaningful departure from the monocentric assumption because their behavior is never considered in any but the most trivial way, and their inclusion has no effect on the solutions obtained from the theories.

If the comprehensive urban transportation studies of the postwar period have done anything, they have made clear the inappropriateness of the monocentric assumption. It is rare that as much as 10 per cent of all employment is located in the core or central business district, and the central city will often contain less than half of all metropolitan employment.[9] In 1963, 52 per cent of all manufacturing and 29 per cent of all wholesaling employment in forty of the largest metropolitan areas was found outside the central city.[10] The fractions are even larger today.

The prevailing trend over the past half century has been a relative and often absolute decline in central employment and a rapid

9. In a recent study of four metropolitan areas Struyk and James defined a "central industrial district" for each area that included the central business district (CBD) but was more extensive. They determined that the share of total SMSA (Standard Metropolitan Statistical Area) manufacturing employment located in these central industrial districts in 1965 was 4.6 per cent for Boston, 14.8 per cent for Cleveland, 7.6 per cent for Phoenix, and 11.1 per cent for Minneapolis-St. Paul. See Struyk and James, "Intrametropolitan Industrial Location," especially Chapter 6. Of course, the representation of other kinds of jobs in the central industrial district is somewhat greater. Using a generous definition of the CBD, the Philadelphia CBD had provided jobs for 117,318 workers in 1960 or 8.3 per cent of 1,437,265 jobs in the SMSA for the same year (*Penn-Jersey Transportation Study*, vol. 2, p. 220).

10. Kain, "Distribution and Movement of Jobs," p. 27.

growth of jobs in suburban areas. Theories that claim to explain the suburbanization of urban populations, changes in the length of the journey to work, and modifications of central and suburban densities without explicit references to these changes in the distribution of employment must be viewed with suspicion. Many of the past changes in urban structure, which these theories attribute to increases in incomes and to declines in the real costs of transportation, may instead be the result of changes in employment location. Existing empirical tests of the theories do not distinguish between these explanations.

Housing Stocks and Long-Run Equilibrium[11]

In addition to evaluating the implications of relaxing the monocentric assumption, we also abandon the highly restrictive long-run-equilibrium framework which characterizes all existing economic theories of location. The long-run-equilibrium assumption makes it possible in these theories to ignore completely the effects of durable nonresidential and residential capital stocks. The omission from existing models of the effects of capital stocks on locational and investment decisions of firms and households may well be the most serious limitation of their value as guides to public policy.

Existing economic theories of location employ the method of comparative statics, which involves the analysis of the distributions of employment, population, income, and other relevant characteristics that would exist in long-run equilibrium. The long-run-equilibrium state that is assumed in these theories is a fairly metaphysical concept that requires a full adjustment of the capital stock to any changes in supply or demand conditions.

Long-run-equilibrium models provide no information about the process of stock adjustment or the time path of adjustment. Furthermore, the equilibrium state is assumed to be independent of the path of adjustment. Of course, the failure to consider explicitly dynamic adjustment mechanisms is a general weakness of economic theory and analysis. However, because capital stocks are especially

11. A more detailed treatment of the issues discussed in this section is contained in chapters 3 and 4.

important for urban housing markets, this general weakness of economic theory and analysis is particularly serious in the analysis of urban development.

The implication of the long-run-equilibrium assumption used in existing economic theories of location and urban spatial structure is perhaps better illustrated by an analogy. In effect, in existing theories of location it is assumed that either cities are destroyed every night and rebuilt the next morning or that households live in house trailers that are relocated daily. In either case, the size, location, quality, and distribution of dwelling units are assumed to adjust instantaneously (or at least quickly) to changes in income, employment location, population, tastes, transportation, and other forces. As a consequence, the long-run-equilibrium values of population and distributions of employment, population, housing, and the like are appropriate.

It is obvious that this view cannot be literally correct.[12] In fact, cities never reach the equilibrium position these models describe.[13] Stocks of nonresidential and residential capital may last hundreds of years. It may be more correct to assume that capital stocks have infinite lives and that they are in a state of perpetual disequilibrium.[14]

In considering this question, it is useful to think of two kinds of outlays by firms and households. The first of these is for the construction of new structures. New construction combines vacant land, labor, and materials to produce a durable structure of rather well-defined characteristics. The second kind of outlay consists of periodic expenditures to maintain the structure. Once the structure has been built, it can be kept in its original condition with modest annual outlays. In addition, some changes in the characteristics of structures are possible. However, there is a limit to the extent of these modifications, and certain types of changes can be achieved only (most cheaply) by demolishing the existing structure and using the vacant land in the production of an entirely new structure.

Once a structure with specific characteristics exists at a particular

12. See Muth, *Cities and Housing*, for an excellent defense of these models.

13. A further discussion of this question is contained in Brown et al., *Empirical Models*, Chap. 7.

14. See Harrison and Kain, "Historical Model," for an example of an econometric model based on this opposite view.

location, the market price of the structure and of the land beneath it depends entirely on the demand for the services it provides or its value in some alternative use. In deciding whether to make further investments in the existing structure, the owner considers only the incremental benefits and costs associated with those new outlays. The historic investment in the structure is not relevant; it is a sunk cost. Before the structure will be replaced by a new structure, the expected discounted future benefits (revenues) of the new structure must exceed the present value of the expected future net returns from the existing structure plus demolition costs plus the capital costs of the new structure.

New construction on vacant land is an alternative to construction on occupied sites. To demolish an existing structure to make way for new construction, the differential net revenues from constructing the new structure on the built-up site instead of a vacant site must exceed the discounted present value of future net receipts obtained by continuing the structure in its current use plus demolition costs minus the cost of vacant land. In other words, the cost of built-up land is equal to the discounted present value of the expected net revenues from the property in its current use plus demolition costs.

As a result, stocks of nonresidential and residential capital in cities are seldom demolished and replaced by new structures. Furthermore, the stocks of nonresidential and residential capital have a powerful effect both on the types of new investment and on their location. New construction will be concentrated on those types of housing services that are not easily or cheaply produced from the existing stock of residential capital. Except when there are significant locational advantages, new construction will occur on vacant land—most of which is found at the periphery of the built-up area. The result is that the spatial distribution of housing capital of different types will depend on the timing of development and will differ from that which would occur if the city were built anew each year.[15]

In the NBER Urban Simulation Model stocks of residential capital are explicitly represented. The model does not yield the long-run-equilibrium distributions of residential capital consistent with the existing levels and distributions of employment, incomes, tastes,

15. Evidence for this position is contained in Harrison and Kain, "Historical Model."

transportation costs, and other factors believed to influence the quantity and location of housing services consumed by urban households. Instead, it yields estimates of the desired demand for housing by type and location during each time period. The existing stock is modified by maintenance, renovation, repair, and new construction. Moreover, the prices that determine the desired demand in each period are not long-run-equilibrium supply prices, but rather are a set of expected market prices that reflect the composition and location of existing stocks of residential capital.

Heterogeneity of the Stock

A major advantage of the long-run-equilibrium assumption is that it permits the theorists to ignore all aspects of the heterogeneity of housing except location and price. In the long run any kind of housing can be produced at any location within the metropolitan area at its long-run supply price. A consequence of this homogeneity assumption is that economic theories of location and urban structure yield only a single price gradient for urban land. Since nonland factors of production are assumed to cost the same everywhere in the metropolitan area, housing prices vary from one part of the region to another only because land prices differ. However, once durable stocks are included in the model this condition no longer holds, and no simple relationship exists between the price of various types of housing and their location within the region.

Therefore, in the NBER Urban Simulation Model the relative prices of different types of housing are permitted to vary from one part of the region to another. Furthermore, NBER studies by Straszheim for San Francisco, by Kain and Quigley for St. Louis, by Ingram for Pittsburgh, and by Quigley for Pittsburgh indicate the situation is more complex than simple economic theories of location assume.[16] All of these analyses indicate that there are different price gradients for different housing attributes or for discrete housing types.

Existing economic theories of location recognize two attributes of

16. Straszheim, "Demand for Housing Services"; idem, "An Econometric Analysis"; Kain and Quigley, "Discrimination and a Heterogeneous Housing Stock"; Ingram, "Model of a Housing Market"; and Quigley, "Residential Location."

housing services at most: accessibility to the center and the quantity of residential space consumed. However, it is apparent that the bundles of residential services consumed by urban households consist of a large number of additional attributes. Many of these attributes are difficult to modify by the actions of individual property owners and collective action of some sort is therefore required.

To allow for a wide range of housing attributes, the NBER Urban Simulation Model defines a series of housing submarkets within which housing services are assumed to be homogeneous. The Detroit Prototype contains 27 distinct housing types (submarkets) defined in terms of structural type, number of rooms, and dwelling unit–neighborhood quality. The housing submarket definitions used in the Detroit area are only tentative. We know the model's validity would be greatly increased by better submarket definitions and are actively at work trying to improve these submarket definitions. As is discussed in chapters 8 and 9, the problem is easier to describe than resolve.

Problems of Interdependence

Especially vexing problems of heterogeneity arise from consumption externalities, from the public provision of local public goods, and from other so-called neighborhood effects. Our analyses indicate that housing attributes that are in some sense external to the particular property or dwelling unit (the quality of local public schools, neighborhood crime, neighborhood prestige, etc.) are as important as attributes of the dwelling unit itself (size, condition, number of rooms, etc.). Existing economic theories of location and urban structure ignore these external dimensions of the bundle of residential services.[17] Unfortunately, the lack of adequate theory, the paucity of persuasive empirical evidence about how these attributes are produced and how they influence household behavior, and the pressure of time have prevented a satisfactory representation of them in the Detroit Prototype.

Research on household demand for these collective housing

17. These issues have been considered in a limited way in Tiebout, "Theory of Local Expenditures"; Rothenberg, "Strategic Interaction"; Ellickson, "Metropolitan Residential Location."

attributes and the determinants of their supply has been a prominent part of all our econometric studies of the housing market. Moreover, the NBER model has great potential for testing various hypotheses about the relationship between individual and aggregate locational decisions. For example, when an individual household makes locational decisions it is influenced by its perception of the present and anticipated quality of public goods in various jurisdictions. But it is just as evident that the quality and types of public goods in a jurisdiction depend on the characteristics of past and present residents of that community. Heretofore, no suitable models have existed for considering these kinds of interdependencies.[18]

Racial discrimination in urban housing markets is an obvious and particularly important type of interdependence. The Detroit Prototype does not include racial discrimination. This results from model-building priorities rather than our evaluation of what is most important. Before introducing any additional complexities, even one as important as housing market discrimination, it is first necessary to have a basic market model.

We have several ideas about how we might represent housing market discrimination in the model and regard this extension of the model as having the highest priority. If a defensible representation of racial discrimination can be devised and incorporated into the model, the most valuable contribution of the NBER model could be its use in evaluating the consequences of discrimination.

The NBER Urban Simulation Model and the RAND Model for the Study of Urban Transportation

While the NBER Urban Simulation research project is only about three and a half years old, the model has been under more or less continuous development for the past ten years. A precursor of the NBER Urban Simulation Model was formulated in the summer of 1961 when John F. Kain and John R. Meyer sketched the design of a large-scale computer model for the RAND Corporation study of urban transportation.[19] Although limits on budgets, time, computer

18. In a second version of the NBER model, neighborhood quality is explicitly incorporated as a housing attribute. See "Characteristics of Pittsburgh I" in Chapter 9, below.

19. Kain and Meyer, *First Approximation.*

capacities then available, and knowledge prevented the construction of the model at RAND, the underlying model design influenced several empirical studies carried out by Kain in the 1960s. However, it was not until September 1968 that active model development was resumed.

A good deal can be learned from this lengthy process of conception, gestation, and delivery. The proposed RAND simulation model was, like the NBER model, conceived of as a policy analysis model for a generic urban area. While the objectives of the RAND and NBER model-building efforts were quite similar, the Detroit Prototype is a far different, and we believe a far better, model than the one proposed for the RAND study of urban transportation. These differences result from the greater knowledge provided by the substantial body of empirical research on urban problems in the ensuing decade, the experience in computer simulation acquired from the Harvard METS (Macroeconomic Transport Simulation) model,[20] the rapid gains in computer technology, and two and a half years of intensive empirical research and model development at the National Bureau of Economic Research.

The principal difference between the NBER model and the model proposed by Kain and Meyer for RAND is that the former contains a much more explicit representation of the housing market. The model proposed in *First Approximation* closely resembled the land-use models used in urban transportation studies during the past decade. It differed from them principally in its greater concern with the theoretical basis of its econometric estimates.

The differences between the RAND and NBER models become apparent when the approaches used in the two models to allocate workers to residence zones are compared. In both models it was assumed that workplace location was predetermined, and great emphasis was placed in both on workplace location in explaining the locational decisions of urban households. However, in the RAND model the allocation of workers to residence zones was to be accomplished using econometrically estimated distribution functions of the type,

$$W(I, J, H)/WT(J, H) = F[X(1), X(2), \ldots, X(N)], \qquad (2.1)$$

20. Kresge and Roberts, *Systems Analysis*.

where the dependent variable is the proportion of the total workers of a particular type, *H*, employed at a particular workplace, *J*, who reside in a particular residence zone, *I*, and where $[X(1), X(2), \ldots, X(N)]$ are a series of explanatory variables describing the characteristics of the residence zone, the level of location rents or housing prices in each residence zone, and the travel time and cost of reaching each residence zone from the particular workplace.

These allocation functions were to be estimated for homogeneous classes of workers, defined in terms of income, race, family size, and other characteristics assumed to have an effect on housing choices. The functions were to be incorporated in the Urban Simulation Model and used to evaluate the effects of changes in the distribution of employment, changes in residence zone characteristics, transportation improvements, and similar changes in the determinants of residential location.

When we began to develop the NBER model, it still seemed likely that the approach depicted by equation 2.1 would be used to allocate households to residence areas. Therefore, Steven Mayo obtained econometric estimates of equation 2.1 for Milwaukee.[21] Although we obtained empirical estimates of the distribution functions proposed in *First Approximation* as a precaution, we were dissatisfied with the approach and continued to evaluate alternative methods.

The technique finally employed includes a linear programming algorithm to help solve this problem. When we began work on the NBER Urban Simulation Model, we regarded the use of linear programming as impractical. However, linear programming continued to have considerable theoretical appeal, provided an operational approach could be devised. After considering and discarding a number of other approaches to simulating supply and demand mechanisms in the urban housing market, we conceived of an operationally feasible way of using linear programming both to locate individual households and to provide location rents classified by housing submarket.[22] This approach, which is completely

21. Mayo, "Econometric Model."

22. The increase in computational speed and the decline in the real cost of computer operations were important considerations. Kain and Meyer considered the use of linear programming to represent the housing market when they were developing the design

different from that advanced by Herbert and Stevens, is described in chapters 3, 4, and 7.

The approach used in the NBER Urban Simulation Model is a closer replication of the theory of demand of microeconomics than was the approach proposed for the RAND study. Household demand for both specific housing types and locations depends on the prices of different kinds of housing at different locations. These prices are determined by input prices and the competition among urban households for particular residence sites.

There are other important differences between the two models. In the RAND model all firms and households were located in each iteration period. In the NBER Urban Simulation Model only a fraction of households are located during each period, and these households compete for only a part of the housing stock. Although Kain and Meyer minimized the importance of the distinction between movers and other households in *First Approximation,* we have come to believe it may be essential to a correct modeling of housing market dynamics. The submarket demand functions are estimated for only recent movers, and we have done extensive empirical research on moving behavior.[23] Much of the complexity of the NBER model results from the need to identify movers, to vacate dwelling units, and to adjust workplace populations and housing stocks to reflect these and subsequent changes.

There are a large number of other differences between the two models. However, the preceding discussion and those that follow should indicate the progress which has been made in the art of building urban simulation models during the past ten years.

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described in *First Approximation.* Indeed, Meyer and William Niskanen previously proposed a model which made rather extensive use of linear programming. However, the formulation was considered infeasible for the available computer technology. The largest and fastest computer generally available at the time was an IBM 704. The IBM 360/67 computer used to develop the NBER model dwarfs the IBM 704 in speed and computational power. The IBM 360/91, used for some recent runs of the model is, in turn, another order of magnitude faster.

23. Brown and Kain, "Moving Behavior"; and Fredland, "Residential Mobility."