01 Jan 1972

# Assumptions In Forrester's Urban Dynamics Model And Their Implications

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new activity is made to depend in part on the overall level of activity, so that interesting accelerator-type relations are built into the model. As a final comment one may question the disaggregation of business into new enterprises, mature business, and declining industry, with each firm passing through this life cycle in a mechanistic manner. Although such a classification may be suggestive for some purposes, it is not very easily convertible into an operational definition when one considers the way in which industrial data is collected and presented. In sum, we get the overall impression that the theoretical foundations of the model received minimal attention.

Forrester's disinterest in modeling a particular city aggravates this. There is no attempt to match the initial state, parameters, or behavior of the model to a real city. Thus there is no way to correlate the behavior of his model with the behavior of a real city. A more rational approach is to pick key variables, empirically establish their relationships, and then tune the model to predict the past performance of the system. Finally, to close the loop, the model is used to predict the future. Any divergent results then feed back to correct the model.

This raises the question of making changes in the model. For example, if the business sector is modified, how is the new model validated? Is it necessary to run all of Forrester's experiments again and carefully check their results? Clearly the answer is yes. Now suppose ten man-years are invested in developing a "better" model. Then one day a small change is made. Is it necessary to repeat the ten years of validation procedures?

If there is to be any hope of building on the work of others, models must be designed in a modular fashion. One should be able to say: "This is a model of the housing sector. If you change the business sector, it won't affect the validity of the housing sector model." The development of modules will also allow more complex models. Forrester's model is a gestalt; it was conceived and built by one man. It might be said that it is as far as one man can go. More complex models will have to be decomposed into sectors, with a different group working on each sector.

In order to achieve this it will be necessary to develop rational validation schemes for modules. One cannot hope to test the module explicity for each situation. If no such validation is possible, it brings into question the major premises of Forrester's work: that it is possible to understand and to express the local properties of a large system in mathematical terms, and by so doing to describe its global behavior.

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# Assumptions in Forrester's *Urban Dynamics* Model and Their Implications

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***Abstract*—Forrester's *Urban Dynamics* model is examined in terms of 1) his assumptions about complex dynamic systems, 2) the *a priori* bias revealed using a "normalized" model, 3) equilibrium changes when the model is modified to fit urban data, and 4) policy predictions of such a modified model.**

Manuscript received August 31, 1971. This paper was presented at the Second Annual Pittsburgh Conference on Modeling and Simulation, Pittsburgh, Pa., March 29–30, 1971. This paper is part of a dissertation submitted to the University of California, Los Angeles, in partial fulfillment of the requirements for the Ph.D. degree.
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## Introduction

THE PUBLICATION of Forrester's *Urban Dynamics* [4] in 1969 has produced a substantial reaction on the urban and academic scene. Through the use of an ingenious and complex new model, Forrester predicted that the public programs presently being used to attack urban problems were not helpful, indeed often harmful. Only drastic new programs, based largely on demolition of slum housing, would solve the problem.

The deserved renown of Forrester's earlier work, the prestige of his institution, and the cold credibility of computer printout added substantial weight to his conclusions. Reviews sprang up in newspapers, magazines, and disparate journals; some praised the work, others criticized at least in part. Critiques, analyses, extensions, theses, and dissertations covering the model sprang up independently at uncounted institutions across the country; the ten papers presented at the Second Annual Pittsburgh Conference on Modeling and Simulation formed only a representative sample of this work.

Each author takes a different approach to evaluating or extending the *Urban Dynamics* model. My own in this paper is to examine in detail the assumptions on which the model is based and their impact on model performance and predictions. Some of these assumptions are implicit in the selection of "industrial dynamics" as the modeling methodology, and others in Forrester's hypotheses about urban systems; both of these are reviewed. Most of the assumptions creating the model are bound up in the myriad choices of constants and relationships between variables necessary in model development. These are examined in three ways: 1) by observing what a "normalized" version of the model teaches us about *a priori* bias built into the model; 2) by comparing the model in detail to urban literature, making indicated changes in the model, and observing the effect of this modification on model dynamics and equilibrium; and 3) by applying tests of simulated public policies to the modified model to see how its predictions differ from those of the original model. The analysis in this paper is derived from my recent dissertation [1] except for the public policy tests, which represent new unpublished work.

This paper is admittedly incomplete without at least a summary description of the basic *Urban Dynamics* model being analyzed. For brevity I shall dispense with such a summary and assume some familiarity on the part of the reader. The serious reader is invited to review the original work [4] and some of the references cited at the end of this paper.[1]

## Assumptions Implicit from Industrial Dynamics

Professor Forrester is deservedly famous for his "industrial dynamics" approach to the modeling of complex dynamic systems, an approach best described in his 1961 text of the same title [5]. In the past decade Forrester and his associates have had singular success in applying the same techniques to many complex systems, leading Forrester to wonder if an urban system might not respond to the same treatment. In his own words [4, pp. 9–10],

> This study of urban dynamics was undertaken principally because of discoveries made in modeling the growth process of corporations. It has become clear that complex systems are counterintuitive .... The likelihood that these same counterintuitive processes might be at work in a system as complex as a city provided the major incentive for undertaking this study.

[1] For a brief description of Forrester's *Urban Dynamics* model see [6].

Over the years Forrester has formulated a comprehensive theory of the nature of complex dynamic systems. This theory may be abstracted [1, pp. 280–288] rigorously from *Urban Dynamics* as a consistent set of axioms, hypotheses, and the like. Summarizing this theory a *complex system*: a) is a high-order multiple-loop nonlinear feedback structure; b) contains both negative (goal seeking) and positive (growth generating) feedback loops; c) is counterintuitive; d) is remarkably insensitive to many changes in system parameters; e) stubbornly resists most policy changes; f) is highly responsive to a few guiding policies which are often not obvious; g) largely counteracts external corrective effort by reducing corresponding internal activity; and h) often displays short- and long-term reactions to policy change that are in opposite directions.

Similarly, Forrester defines a *dynamic system* as one that changes through time, and states that it must contain four "hierarchies of structure": a) a closed boundary around the system; b) feedback loops within the boundary; c) level (state) and rate (flow) variables within each feedback loop; and d) action based on discrepancies detected between some goal and an observed condition to change the rate variables.

## Assumptions About Urban Systems

Forrester postulates explicitly [4, p. 1] that an urban area is a complex dynamic system meeting the aforementioned criteria whose life cycle may be studied using the methods of industrial dynamics. He therefore expects the dynamics of an urban area to be counterintuitive and is unsurprised by model predictions supporting policy recommendations at variance with current urban thought. I would agree instead with Kadanoff [8] that "the main policy recommendations of *Urban Dynamics* are in no sense counterintuitive; they follow directly from Forrester's implied normative scheme" which is imbedded in the model structure.

Since Forrester assumes that urban systems are insensitive to all parameters except a few "guiding policies," he tends to assign values uncritically to a number of parameters and relationships which, I have found, exert considerable influence on model predictions. And since his parameters were developed from discussions between men of "practical experience in urban affairs" without any apparent reference to urban literature, it is not surprising to find values assigned which vary widely from accepted urban data.

By assuming a) the purpose of the model is to simulate urban growth, stagnation, and revival, b) a good simulation model contains within its boundaries all those (and only those) components that generate the behavior of interest, and c) the changes in housing, population, and industry are the central processes in growth and stagnation, Forrester not only defines the scope of his model but also reveals his assumptions about the processes critical to urban change. Forrester also assumes that the world may be effectively dichotomized into a portion of a city (the "specific land area" within his system boundary) and the rest of the world (the "limitless environment"). This assumes that a core city can be modeled with no closer relationship to the contiguous urban fringe than to the rest of the world. I would agree instead with Hester [7, p. 4] that "models of urban development . . . need to incorporate . . . strong interactions between one part of the city and the remainder of the urban area."

Critical both to the "inevitable condition" of the mature city Forrester predicts and the slum demolition he recommends to counteract it is the assumption that housing availability is as important as job availability in attracting unskilled in-migration (compare [4, pp. 140, 143, figs. A-3, A-5]). I have analyzed this elsewhere [2] and conclude from examination of available literature that the influence of housing availability is far weaker than Forrester has assumed it to be.

## Lessons from a "Normalized Model"[2]

The *Urban Dynamics* model includes a wide range of arbitrarily assumed constants, and the choice of these constants represents a set of assumptions (deliberate or accidental) about the urban condition. These constants are then multiplied by the product of a series of "multipliers," each representing the effect of some variable thought to influence the parameter being calculated. A convenient way to examine the effect of the constants chosen is to assume that the model exists momentarily in an artificial condition in which all multipliers take on their "normal" or central value of 1.0. For example, the rate of annual decline from new enterprise (NE) to mature business (MB) is modeled by Forrester as the product of 0.08 and five "multipliers" expressing the effect of land, skilled labor and entrepreneur availability, tax level, and recent growth history; in the "normalized" condition each of these multipliers is assumed equal to unity. The following additional assumptions are made to construct the normalized model.

1) Existence of 8.025 units of NE.
2) Existence of just enough MB (12.84 units) and declining industry (DI) (21.40 units) so that new enterprise decline (NED), mature business decline (MBD), and declining industry demolition (DID) all have the same value (0.642 units/year) when all multipliers are unity.
3) Exactly enough workers of all kinds to staff the preceding industry (929.5 workers) and to construct the desired NE and housing (70.5 workers). This adds up to 1000.0 workers, of whom 7.9 percent are managerial–professional (MP), 61.4-percent skilled labor *L*, and 30.7-percent unskilled labor *U*.
4) Exactly enough housing of each type (premium housing (PH), worker housing (WH), underemployed housing (UH)) to house these workers.

Given this normalized model, one may then examine its tendency to depart from this normalized condition. One

[2] A more detailed development of this "normalized model" may be found in a recent paper [3] and in my dissertation [1, pp. 201–300].

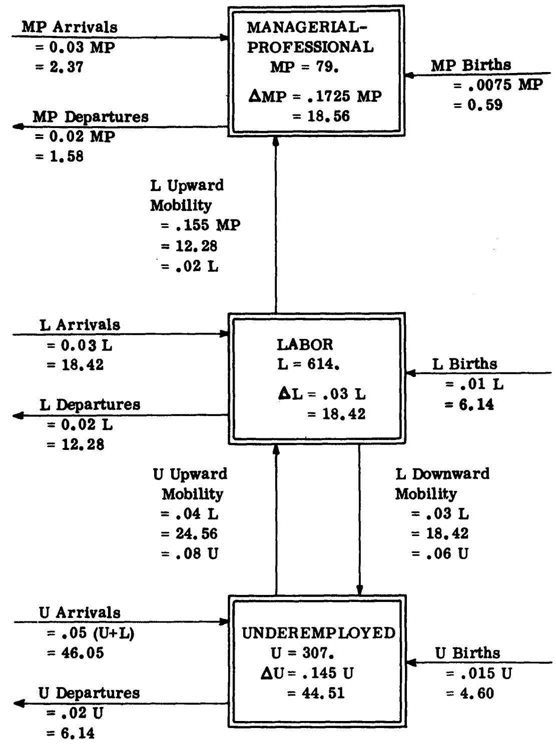

Fig. 1. "Normalized" work force sector.

observes the following.

5) NE is being constructed at a 9.39-percent annual rate, yet decays only at a 6.42-percent rate. This difference provides the basic growth dynamic to the model and is reduced as land occupancy increases.
6) Workers are increasing at the uneven annual rates (see Fig. 1) of 17.25 percent for MP, 3.0 percent for *L*, and 14.5 percent for *U*.
7) Although PH is essentially stable, WH is increasing at a 1.34-percent annual rate and UH at a 4.0-percent annual rate. Note that Forrester's recommended urban programs of reducing ("discouraging") worker housing by 1.5 percent per year and providing additional slum housing demolition of 5.0 percent per year nicely counteract this imbalance. Yet Forrester makes no effort to show that the "problem" he is "correcting" exists in a real city, rather than simply being created in the model by capricious choice of constants and relationships.

From these observations we would expect the model to predict at equilibrium a substantial excess of *U*, "UH," and MP. Of the first two, Forrester states [4, p. 121] that "the natural condition of the aging city tends toward too much housing and too few jobs for the underemployed population"; on the third excess (MP) he is strangely silent. But we can see from the normalized model that neither this "natural condition" nor the steps Forrester suggests to improve it are counterintuitive; they are implicit in the structure chosen for the model.

TABLE I
EFFECT OF MODEL MODIFICATIONS

| Symbol | Ratio | Original Model | Modified |
|---|---|---|---|
| UHR | Underemployed/underemployed housing | 0.812 | 0.957 |
| UR | Underemployed/job | 1.809 | 1.058 |
| LHR | Labor/worker housing | 1.170 | 1.065 |
| LR | Labor/job | 0.973 | 1.091 |
| MHR | Manager/premium housing | 1.068 | 1.147 |
| MR | Manager/job | 1.380 | 1.140 |

## OBSERVATION FROM URBAN DATA AND MODEL MODIFICATION

In my dissertation I examined each of the 140 equations in the model with some care and compared them where feasible with the urban literature. In this comparison I identified many changes in the model that would make it more consistent with urban data. I transformed the *Urban Dynamics* model to Fortran and then incorporated many of these changes in a series of six steps to observe their impact on model dynamics and equilibrium. The following were the most critical changes among the many made.

1) Forrester models unskilled in-migration as 0.05 $(L + U)/U$, providing a 15-percent annual in-migration rate when $L$ is twice $U$. Urban data suggests this rate should be about 3 percent. Out-migration and birth rates also appeared biased in the direction of increasing the unskilled population. When demographic constants for the three types of labor were adjusted consistent with census data, the annual increase predicted by the normalized model (see Fig. 1) for MP became 9.12 instead of 17.25 percent, for $L$ became 3.26 instead of 3.00 percent, and for $U$ became $-2.45$ (a decrease) instead of 14.5 percent. And when these figures were incorporated into the Fortran model, the equilibrium unemployment of the unskilled dropped from 45 to 23 percent.

2) In the Forrester model 93 percent of employment is industrial (at least in the model logic associated with it) and the other 7 percent is in construction. In my modified model only 42.6 percent of "normal" employment was assumed in these two categories to be consistent with the "typical" U.S. city. The other 57.4 percent was placed in two categories controlled by population and by a combination of population and income. Further, Forrester's "normal" proportions of MP/$L$/$U$ workers were 0.079/0.614/0.307. I changed this to 0.132/0.479/0.389 after interpreting Bureau of Labor Statistics data.

3) Forrester makes obsolescence of housing and decline of industry depend only on "supply" conditions in the higher use category (WH, for example). I made it depend also on "demand" conditions in the lower category (UH, for example). Forrester also assumes that high land occupancy and high taxes accelerate this rate of obsolescence or decline; I saw no justification for this and deleted it.

When these and other (less critical) modifications were made in the model (producing my "changes 1–6" version, [1, pp. 161–165]), the effect on model equilibrium was as shown in Table I. As a result of these changes, made in an objective attempt to make the model more consistent with urban theory, the excesses ($U$, UH, MP) predicted by Forrester largely disappear. No claim is made that the modified model accurately represents the urban condition. I do claim to have shown, however, that the "inevitable condition" predicted by the original model is created by *a priori* assumptions built into the model as a bias with no effort at their justification.

## TESTS OF URBAN PROGRAMS IN MODIFIED MODEL

After creating his model of the urban area, Forrester tests the effects of a series of possible urban programs by simulating them in the model. He does this by perturbing the equilibrium reached by the model after 250 simulated years with one or more parameter changes, and then observing the effect of these changes over the next 50 years. He concludes that most conventional or "intuitive" programs actually worsen the urban condition. Only combinations of slum housing demolition (SHD), discouragement of WH, and encouragement of NE give promise of urban revival. Since my modified model predicted a different urban equilibrium and somewhat different dynamics, it might be expected to predict somewhat different reactions to urban programs. I have tested this by perturbing the modified model equilibrium with the same 11 programs tested in [4, chs. 4 and 5] and observing the effect over 50 simulated years.

*Underemployed Job Program:* In this program jobs are provided exogenously for 10 percent of $U$. Many critical parameters change in the same direction as in Forrester's model over the next 50 years, but only one-half to two-thirds as much. For example, NE decreases 4.6 percent, the $U$ population rises 6.7 percent, and the tax rate needed rises 7.6 percent. $U$ unemployment, however, almost disappears (down from 17 000 to 3600), whereas it rises slightly in Forrester's model. I ascribe the difference largely to a more realistic normal unskilled in-migration rate (Forrester's UAN) in the modified model.

*Underemployed Training Program:* Under this program 5 percent of $U$ are transformed into $L$ each year through training programs. Effects in the two models are similar. The original and modified models act as "trade schools," accepting 17 000 or 11 000 unskilled students, respectively, per year through in-migration, upgrading them, and "graduating" the same number through $L$ out-migration. Forrester considers this a burden to the city but a service to society. However, if the total environment consists largely of urban areas such as this, their skilled "graduates" really have no place to go, and the model is deficient. To be more realistic, this policy should be tested in a model which reflects a) the ability of the "environment" to absorb out-migrating workers, and b) the technological trend of increasing relative demand for $L$.

*Financial Aid:* This program assumes that \$100 per person tax subsidy is provided exogenously at no cost to the city. In the original model the only significant effect of financial aid was an increased $U$ population without increase in employment for them and an increase in tax need despite the subsidy. In the modified model all worker classes increased about 6 percent, as did premium employment (NE and MP). Housing of all types increased less than 1 percent, causing over-crowding, and DI decreased 3 percent. Even in the modified model the city is not better off (just more crowded), and if this city is "typical" of all others, the question of who is providing the tax subsidy is hard to answer.

*Housing Construction:* The low-cost housing program intends to increase low-cost housing by 5.0 percent per year through externally financed programs. Due to land shortage only a 3.0 percent annual increase is being achieved in the original model and a 1.2-percent increase in the even more crowded modified model by the fiftieth year. In the original model changes are drastic: premium (NE and MB) industry decrease 47 percent, premium (MP and $L$) workers decrease 31 percent, and $U$ unemployment climbs 30 percent. In the modified model changes are much less drastic ($-12$, $-5$, $+9$ percent). In both cases changes depend on the *a priori* (and unsupported) assumption that excess low-cost housing provides a powerful magnet for attracting unskilled in-migration. Further, if low-cost housing construction takes place in most cities, the relative attractiveness of a given city should not be much affected.

Programs designed to increase worker housing by 2 percent per year and premium housing by 5 percent per year were also tested in the modified model. Results were generally consistent with those in the original model, considering the higher land occupancy in the modified model.

*New Enterprise Construction (NEC):* This program attempts to create annually through some undefined technique additional NE equal in number to 2 percent of the existing productive units (PUT = NE + MB + DI). The actual construction program (NECP/PUT) is only 1.06-percent annual increase in NE for the original and 0.65 percent for the modified model because of land shortage. A few critical parameters are identified in Table II. A few comments seem justified. Although the construction program increases NEC about 50 percent in both models, total NE is only up 21 percent after 50 years in the original. This is because the average NE lifetime is only 5930/704 or 8.4 years since land shortage is assumed to accelerate its decline to MB. The modified model deletes this questionable provision, producing a lifetime of 4210/278 or 15.1 years. The total productive units (NE + MB + DI) of 39 600 in the original and 17 800 in the modified model are reasonably equivalent since industrial employment is assumed to provide only about 40 percent of jobs in the modified model. Finally, the existence of 47-percent more $L$ and 9-percent less $U$ than the corresponding housing stock in the original model seems inconsistent with the relative purchasing power of these groups. Provision of a demand factor in housing filtering makes this behavior more realistic.

TABLE II

Effect of New Enterprise Construction Program (NECP)

| Parameter | Original Model Time (years)[a] $-5$ | 50 | Change (percent) | Modified Model Time (years)[a] 0 | 50 | Change (percent) |
|---|---|---|---|---|---|---|
| NECP | 0 | 418 | — | 0 | 115 | — |
| NEC (total) | 462 | 704 | +52 | 189 | 278 | +47 |
| NE | 4900 | 5930 | +21 | 2800 | 4210 | +50 |
| MB | 7800 | 9930 | +27 | 4450 | 6560 | +47 |
| DI | 16 500 | 23 730 | +44 | 5400 | 7070 | +3 |
| Workers (MP + $L$ + $U$)[b] | 841 | 1028 | +22 | 876 | 1063 | +23 |
| LHR | 1.17 | 1.47 | +26 | 1.065 | 1.273 | +20 |
| UHR | 0.81 | 0.91 | +16 | 0.957 | 1.167 | +22 |
| Land fraction occupied (LFO) | 0.82 | 0.86 | +5 | 0.88 | 0.92 | +4 |

[a] New enterprise construction program is instituted at time zero when city is at equilibrium.
[b] Thousands.

*Declining Industry Demolition:* In this program 5 percent of DI is demolished annually. In both models DI decreases 60 percent over 50 years, decreasing land occupancy 2–3 percent, and taxes 9 percent. In the original model NE and MB increase 25 percent, half due to increased NEC and half due to longer NE life with lower land occupancy. The second factor does not apply in the modified model, and NE and MB change very little.

*Slum Housing Demolition:* In this program 5 percent of existing underemployed housing is removed each year. NE increases 45 percent in the original and 36 percent in the modified model to fill some of the vacated space. In the original model both $L$ and worker housing construction (WHC) increase 34 percent. In the modified model $L$ increases 16 percent, but the WHC rate increases 40 percent to permit faster filtering to unskilled occupancy to replace the "slum housing" demolished, a process which would of course occur.

In the original model this program predicts a decrease from 45 percent down to 17 percent $U$ unemployment at the cost of 21 percent overcrowding in unskilled homes . . . a significant improvement. In the modified model, however, the unskilled have only 5 percent unemployment and 4 percent excess housing to begin with. After 50 years of slum demolition there are 44 percent more $U$ than houses and 15 percent less $U$ than jobs. If the city corresponds to the modified model, therefore, SHD would be both economically unnecessary and politically impossible.

Two other runs were made in which SHD was combined first with a discouragement of WHC and second with encouragement of NE. The trends observed for SHD alone were accentuated in these combined policy runs, and the same comments apply with increased vigor.

## Extension to Two-Subsystem Model

In analyzing the model I began to doubt that an urban core of fixed area could be properly represented without some feedback relationships to the continuous growing portions of the city. I therefore prepared a preliminary version of a two-subsystem model to represent this relationship. As the model representing the "urban core" subsystem began to fill its alloted land area, I allowed it to interact with a similar model, initially much less populous, but modified to provide continuing growth and somewhat lower density. The two subsystems were interrelated through "tax sharing" (equilibrium of tax rates), residential relocation between the two subsystems, and commuting within specified distances dependent on job opportunities.

The effect of "tax sharing" between the two simulated subsystems was to increase somewhat the proportions of *L* and MP and the level of NE in the urban core at the cost of a modest decrease in the growth rate of the other subsystem. Relocation and commuting, on the other hand, appear to increase the relative proportion of the underemployed in the urban core, although the UR ratio is reduced through commuting. While it would be unwise to rely very heavily on the two-subsystem model in its present preliminary stage, it seems clear that the two-subsystem model approach can considerably enrich the capability of the model to simulate an urban core area.

## Conclusions

While this paper is in a sense a summary of work documented elsewhere, it seems appropriate to close by restating a few of the major conclusions for emphasis.

1) Neither the equilibrium urban condition predicted by the *Urban Dynamics* model nor the programs recommended to improve it are counterintuitive; they follow directly from the model's assumptions and structure.

2) The "natural condition of . . . too much housing and too few jobs for the underemployed population" represents an *a priori* assumption and is created in the model by biasing model constants and structure. When the model is modified to fit urban data these excesses largely disappear.

3) The power Forrester ascribes to the influence of housing availability on unskilled migration is far greater than can be justified by urban literature; this factor is critical to the urban equilibrium he predicts and the public policy he recommends.

4) The assumption that high land occupancy and tax levels accelerate housing obsolescence and business decline has a significant effect on public policy tests on the model; research to determine this effect is suggested.

5) Lack of provisions in the model to represent the close interaction between an urban core and the surrounding urban fringe severely weakens the model's predictive power.

6) Application of public policy to a single city in an unaffected environment is in general unrealistic. Questions, such as, who hires the skilled "graduates" the city trains, who pays a tax subsidy, who accepts unskilled persons forced out by slum demolition, remain to haunt us. A national model representing a closed system (except perhaps for modest immigration) seems essential. It may be possible to simplify this model into as few as three subsystems: a) a composite urban core, b) a composite urban fringe, and c) a composite rural hinterland.

7) In connection with the national model in 6), some time variance in model parameters to reflect changes in the need for skilled workers and changes in the relative urban/suburban/rural population also seems essential.

In closing I must agree with Kadanoff [8] that "despite these criticisms of Forrester's conclusions, I would argue that his model-making is so brilliant and beautiful that his ideas are certainly worthy of examination and further development. I would reject the conclusions but accept the model as an appropriate basis for further work."

## Nomenclature

| | |
|---|---|
| DI | Declining industry. |
| DID | Declining industry demolition. |
| *L* | Skilled labor. |
| LFO | Land fraction occupied. |
| LHR | Labor/worker housing ratio. |
| LR | Labor/job ratio. |
| MB | Mature business. |
| MBD | Mature business decline. |
| MHR | Manager/premium housing ratio. |
| MP | Managerial–professional. |
| MR | Manager/job ratio. |
| NE | New enterprise. |
| NEC | New enterprise construction. |
| NECP | New enterprise construction program. |
| NED | New enterprise decline. |
| PH | Premium housing. |
| PUT | Productive units total. |
| SHD | Slum housing demolition. |
| *U* | Underemployed. |
| UH | Underemployed housing. |
| UHR | Underemployed/underemployed housing ratio. |
| UR | Underemployed/job ratio. |
| WH | Worker housing. |
| WHC | Worker housing construction. |

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