URBAN SYSTEMS STUDY OF MELBOURNE

Ron Sharpe, John F. Brotchie, and A. Ray Toakley,
Commonwealth Scientific and Industrial Research Organization, Australia; and
John W. Dickey, Virginia Polytechnic Institute and State University

This paper deals with an urban systems study for the future development of Melbourne, a city that has 2.4 million people and is expected to have 5 million by 2000. The ultimate aim of the study is to develop a sketch planning methodology and set of models to facilitate the selection of the best growth patterns for future development; as many quantifiable and nonquantifiable factors as possible were taken into account. The focal point of this particular substudy is a general planning model developed to optimize land use allocation on the basis of some quantifiable benefits and costs. The general model allocates activities to zones and financial resources to activities over several time periods. The benefits and costs include those for travel among activities and for location of activities in certain areas. Some nonquantifiable benefits and costs are introduced subjectively using sensitivity analysis techniques. The model has been specialized to urban planning by inclusion of submodels for such aspects as trip distribution, land values, and building costs. It has been calibrated to Melbourne data in a cooperative effort between the planning authority and the research team, and preliminary information for urban planning decisions is now being produced.

•THE model discussed in this paper deals with urban planning and its attempts to bring about public benefits. The sum of the parts is not necessarily equal to the whole, however. Millions of personal decisions of maximum benefit to each individual do not necessarily make for total maximum benefit. Webber provides good examples of this situation relative to the automobile (2):

> The most obvious example within the transport sector attaches to the growing problems of air and noise pollution. Noxious emissions from individual vehicles are harmless; the problems arise only when the number of individuals gets counted in the millions. . . .Externally, a few motor cars in the streets of the great cities of Europe do not really matter very much. When the numbers become large, the subtle qualities of the cities are rapidly eroded, to the loss of residents and visiting admirers as well.

Owen uses the very descriptive term, "the accidental city" (1), which is connotative of the way in which cities have developed:

> The basic difficulty of urban growth all over the world is that decisions about the use of urban land are being made by a host of private parties without the guidance of comprehensive plans or community goals.

What is happening is that each individual decision must be made in the context of the ones made previous to it. Although these individual decisions may be optimal in their own regard, they may build on each other organically so as to spiral out of acceptable bounds. Apparently this is what has happened in many urban areas—not necessarily

Sponsored by Committee on Transportation Systems Design.

that the city as a whole has become a comparatively disadvantageous place to live (for if it were, it certainly would be deserted by now) but that there are many disbenefits that could be eliminated if the atomistic approach were given up.

There are many alternative ways to guide urban growth if the concept of the overall public good versus the sum of individualistic goods is adopted. This study focuses on one way: the organization of land use activities to reduce both travel costs and establishment costs for water, sewer, schools, and other publicly supplied services. This is an initial formative attempt at using mathematical programming techniques to determine optimal land use activity patterns with respect to the foregoing costs. (Much has been done in the 2 years since the writing of this paper. The reader is directed to the references at the end of the paper.) If future endeavors using the approach suggested here are successful, it is hoped that some valuable inputs can be made to the development of local, state, and even national land use policies.

STUDY BACKGROUND

In 1970 an urban systems study for the future growth of the city of Melbourne, Australia, was proposed by the Division of Building Research, Commonwealth Scientific and Industrial Research Organization (CSIRO), and initiated under the sponsorship of the Melbourne Metropolitan Board of Works (MMBW), the authority responsible for the planning of future development of the city. Melbourne currently has a population of 2.4 million people (1971) and is expected to have 5.0 million by 2000. Current overall public and private establishment and operating costs in the metropolitan area amount to more than $1 billion per year. Roads and services are under increasing pressure as the area and its population expand. To make matters worse, the metropolitan government has deep financial problems. For instance, water and sewer service payments barely cover the interest on outstanding debts for these services (7). Future growth thus must be directed if the regional government is not to come under an even greater financial strain.

STUDY SCOPE

The basic aim of the overall study is to find the best growth patterns for Melbourne based on as many quantifiable and nonquantifiable benefits and costs as possible. This initial study is set on a macroplanning level. Particular goals of this study include the following:

1. Definition of the type and accuracy of data necessary in the study,
2. Determination of macro land use patterns that are optimum for the metropolitan area over the set of planning periods considered,
3. Determination of possible effects of changes in future locational behavioral patterns, and
4. Consideration of some nonquantifiable factors, such as those involved in the conservation of natural resources and reduction of pollution, and presentation of measures of these qualitative factors in a form that allows them to be weighed against the additional costs and travel times incurred.

URBAN SYSTEMS MODEL

A city may be viewed as being composed of four basic elements:

1. Activities—all of the active and passive occupations and pursuits of the citizens living in the city. These activities may be grouped into subsets for ease of manipulation, e.g., industry, commerce, residential activity, education, recreation, and conservation.
2. Interactions—the flows or movements within and among activities of people including services, goods, information, finance, and pollution.
3. Zones—areas that are potentially suitable for the settlement or establishment of activities.
4. Paths—the routes over which the various activities interact. They take the form of networks of roads, railways, pipes, wires, rivers, and air currents.

Associated with the preceding components are quantifiable and nonquantifiable benefits and costs. These include the benefits and costs of establishing the activities in the zones, the paths and flows, and the maintenance, servicing, and operation of these elements. Included is the cost of subdividing and preparing land, of providing streets and network services, hospitals, schools, and recreation and commercial centers, and of block preparation and buildings. A major item is the cost of transportation and travel.

The measure used initially in this study for the expected benefits of location of a particular activity in a particular zone is the price that participants in that activity are prepared to pay in the market for land. Although there are many obvious and serious drawbacks to the utilization of land value in this manner (of which imperfections in the market is a major one), there are also many advantages. In an open supply and demand situation, people purchasing land will buy when the value they place on a particular block is equal to or greater than the selling price. In a residential area, for example, such values would include the benefits of social desirability, social amenity, recreational amenity, terrain attractiveness, environmental value, future development potential, and accessibility to workplaces, shopping, and external recreational areas. Thus, land value is a good surrogate measure of general desirability of a particular location.

Benefits and disbenefits of interactions in addition to traffic flows have also been introduced. These include the reduction in cost when adjacent zones share the same service trunks and headworks and disbenefits of proximity between activities. One measure of the latter is in land value increment. In addition, there is a time element to the process, which for convenience may be approximated by a series of time periods.

From these observations, it is possible to formulate a model to allocate activities to zones according to some socioeconomic objective subject to certain economic, technical, political, and social constraints. The nature of such a model must be an iterative one because the interactions, benefits, and costs are complex functions of the allocation patterns. Hence, the model may be divided into submodels for allocation, followed by derivation, and suitably damped to force convergence to an optimal solution (Fig. 1).

ALLOCATION MODEL

The allocation model is a modified version of a quadratic programming model developed by Brotchie (8, 9) for optimizing the layout of a group of activities on the basis of maximizing the total sum of benefits less costs of interactions among, and establishment of, given activities. This formulation is an extension of the assignment problem developed by Koopmans and Beckman (10).

The N activities of type i in time period m are of magnitude A_{im}. The M areal zones each have a capacity Z_j and may be filled with a single activity or a mix of activities or only partially filled. The objective function includes the benefits and costs of establishing and operating an activity i in a zone j over several time periods (T).

Any portion, a_{ijm}, of activity i can be allocated to zone j in time period m. The planning problem thus is to select the set of a_{ijm}'s to maximize a measure of merit $U(a_{ijm})$ where

$$\text{Max } U(a_{ijm}) = \sum_{i}^{N} \sum_{j}^{M} \sum_{k}^{N} \sum_{\ell}^{M} \sum_{m}^{T} \sum_{n}^{Y} S_{ijk\ell mn} R_{j\ell mn} B_{ijk\ell mn}$$

$$+ \sum_{i}^{N} \sum_{j}^{M} \sum_{m}^{T} a_{ijm} A_{im} C_{ijm} \qquad \text{(1a)}$$

subject to

$$\sum_{i}^{N} \sum_{m}^{T} a_{ijm} A_{im} \leq Z_j \qquad \text{(all j)} \qquad \text{(1b)}$$

$$\sum_{j}^{M} a_{ijm} = 1 \qquad \text{(all i, m)} \qquad (1c)$$

$$a_{ijm} \geq 0 \qquad \text{(all i, j, m)} \qquad (1d)$$

in which

$S_{ijk\ell mn}$ = volume of interaction between the portion of activity i in zone j and the portion of activity k in zone ℓ for the n th mode of interaction during time period m,

$R_{j\ell mn}$ = length of travel path or travel time between zones j and ℓ for the n th mode of interaction during time period m,

$B_{ijk\ell mn}$ = benefit less cost of a unit of interaction $S_{ijk\ell mn}$ along a unit length of path $R_{j\ell mn}$, and

C_{ijm} = benefit less cost of establishing and operating a unit of activity i in zone j during time period m.

The first constraint (Eq. 1b) ensures that no zone is overfilled, the second constraint (Eq. 1c) ensures that each activity is fully allocated, and the third constraint (Eq. 1d) prevents negative allocations from being made.

The model is a nonlinear programming problem with NMT independent variables a_{ijm} and M + NT linear constraints. The merit function will normally be nonlinear because the arrays S, R, B, and C will be complex functions of the independent variables, to be determined by derivation submodels at each step of the iteration. The method of solution is presented in other papers (3, 11).

SUBMODELS

The submodels are used to predict the interactions, path lengths, and benefits and costs of interaction, establishment, and operation of activities. The overall system has been set up such that the submodels developed initially are relatively crude. It is anticipated that more detailed models will be employed after this sketch planning endeavor indicates the general types of beneficial solutions. Following are examples of the submodels utilized: trip generation, trip distribution, modal split, traffic assignment, trip cost, highway network construction and maintenance cost, service cost other than traffic, and land value increment.

In the current study of Melbourne, several of the preceding submodels have been developed to a level worthy of comment and are described as follows.

Trip Distribution Submodel

The submodel used for trip distribution is of the gravity type. The flow generated by an activity i in zone j to an activity k in zone ℓ for the n th flow mode over the m th time period may be assumed (12) to be given by

$$S_{ijk\ell} = P_{ij}\, Q_{k\ell}\, F_{ij}\, F_{k\ell}\, f(B_{ijk\ell}) \qquad (2)$$

where

F_{ij} = number of trips generated by activity i in zone j,

$F_{k\ell}$ = number of trips attracted by activity k in zone ℓ,

$P_{ij} = 1/\sum_{\ell} Q_{k\ell}\, F_{k\ell}\, f(B_{ijk\ell})$, (3)

$Q_{k\ell} = 1/\sum_{j} P_{ij}\, F_{ij}\, f(B_{ijk\ell})$, (4)

$f(B_{ijk\ell})$ = cost and time function influencing trip length = $e^{-\beta t_{ijk\ell}}$, and (5)

$t_{ijk\ell}$ = trip time between zones j and ℓ.

Service Cost Submodels

Services such as water, sewerage, drainage, telephone, electricity, and gas have similar characteristics. They usually consist of source(s) or sink(s) (headworks), a network of trunks or mains or both, and a distribution network.

The staging of headworks and trunks is of major importance in the growth of a city and is highly dependent on the pattern of development. Distribution costs may vary from zone to zone but may be assumed to be relatively independent of development in other zones.

In the proposed submodel, the potential trunk network is assumed for a full set of zones and headworks. The network may then be modified to suit different development patterns by the omission of links and headworks or by changes in their capacity during a time period. Thus, with respect to the first time period, for example, each link and headwork may have one of five state conditions: built during the first time period, built later, partially built during the time period and upgraded during later time periods, already existing, and not to be built at all. Other models are required to calculate the costs of establishing each set of headworks; the cost of building each link as a function of link capacity, terrain conditions, and staging; the flow in each link of a network; and the cost per unit activity of distribution networks as a function of local terrain.

Land Value Increment Submodels

Current land values are available from various sources, and records of land transactions provide hard data in this area. Predictions of land values in future time periods will vary with time and with development and expectations of development.

Two approaches are being followed in the present study. The first is to neglect future land value increments, as a first approximation, or to project them simply from present trends. The second is to build a predictive model based on amenity changes and calibrated on previous data. This second model can then allow for changes in land value with activity allocations in an iterative process. This second approach now is being formulated and the corresponding models calibrated.

GENERATION OF AN INITIAL FEASIBLE SOLUTION

An initial feasible solution needs to be generated at the start of the iteration process. This can be readily accomplished by using any random solution that is not feasible, i.e., one that does not obey the constraints (Eqs. 1b and 1c), and the first step of the iteration process to generate a feasible solution. Alternatively, an initial solution may be generated by the planning authority using conventional planning techniques. Such a solution may be technically evaluated and compared with the optimum solution generated from it.

SENSITIVITY ANALYSIS

A sensitivity analysis may be used to determine the sensitivity of the solution to an increment in a single parameter or group of parameters. The parameter may be a data item, a constraint limit, or an integer type of variable.

In the case of data, it permits the accuracy required of a critical data item or data set to be established by observing the sensitivity of the solution to the item(s). Thus the expense and effort of collecting data may be reduced if the model is insensitive to certain items.

Sensitivity analysis allows the planner to interact with the model. In this way, the planner can control all constraints, data, and certain design variables and allow the model to optimize the remaining design variables. In this way, sensitivity analyses may be used to find the consequences of planning norms and standards, to determine the effects of changes in predictions of population and its behavior, and to determine the effects of future changes in technology or economic structure or nonquantifiable entities. In the latter case, the less tangible factors associated with overall merit (or the weighting placed on them) may be varied and traded off against their economic and technical costs, allowing the directions of an overall optimum solution to be subjectively determined and a course to be set in this direction. A series of these interactive steps would allow the overall optimum to be located approximately.

Long-term use of the model would allow course corrections to be inserted as additional data become available with continuing urban growth. This model, or models of this type, can be used to help develop an effective information system for urban planning. Various developer proposals and strategic decisions may be tested and analyzed, allowing day-to-day as well as long-term decisions to be made taking many consequences into account.

APPLICATION

The study to date has been carried out at a macrolevel by considering aggregations of activities and zones at a coarse-grained level to simplify initial data collection and computer program development.

Three activities have been considered:

1. High-density residential redevelopment at an average increase of 20 people per gross acre;
2. Low-density, new residential development at an average density of 10 people per gross acre; and
3. New industrial and commercial development at an average work force density of 20 workers per gross acre.

Each of the preceding densities is assumed to include development of streets and other public purpose open space. The residential activities also include local shopping, commerce, education, and park land. The residential increase in population is assumed to be 1.2 million by 1985 and split in a ratio of 1 to 3 between high- and low-density development. The increase in work force is expected to be 0.4 million persons.

The city has been divided into 34 zones (Fig. 2), each composed of one or more local government areas. Each is assumed to be homogeneous in character throughout the zone, and all interactions with other zones are assumed to act through the zone centroids of the area. In general, each zone has areas of land vacant and available for one or more of the three activities. The outer zones have large areas of unzoned land available for development, more than that required for development to year 2000.

The interactions among activities considered are the flows of people for journey to work, residential and industrial trips, and the flow of goods among industrial activities. The volume of these interactions has been extrapolated from a 1964 survey carried out by the Melbourne Transportation Committee (13).

The modes of interaction considered are private vehicles and public transport (bus, tram, and train). The 1964 travel-time trees for these modes between the 34 zone centroids have been obtained from the MTC together with the 1985 predicted travel times. At present only a portion of the proposed freeway network is included, but studies shall be made later to ascertain the overall benefits of full upgrading of the freeway and rail networks in stages to the proposed 1985 condition. Associated with each mode of interaction are unit costs of travel, which are functions of travel speed, journey length, and traffic volume.

The costs of establishing services of gas, sewerage, water, local roads and streets, telephone, drainage, schools, and electricity have been assumed initially to be independent of level of development within each zone. These costs have been obtained from the various service authorities on the basis of an assumed 1985 development pattern (8) and reduced to unit per capita costs by dividing the total development cost of each service in each zone by the expected 1985 population increase in each zone. Later, these crude cost estimates will be replaced by using the submodels previously discussed. Land values have been based on records of land sales and averaged in each zone. The land value submodels will later allow for future changes with activity and time.

EXAMPLES OF SOLUTIONS AND SENSITIVITIES

A few examples are presented here to illustrate the results generated by the model. The distributions of activities to zones are shown in the accompanying figures as circles drawn to scale and shaded to distinguish among activities, and Tables 1, 2, and 3 give the per capita costs for each of the examples.

Solution 0 gives the existing work-trip travel times and costs using an uncalibrated gravity trip distribution submodel. After calibration of the submodel (currently being undertaken), it is expected that these costs and times will increase because the activities are not as homogeneous in the real-life situation as assumed in the study. After allowing for errors due to nonhomogeneity, however, it is interesting to note the relative orders of magnitude of the different interaction costs and travel times.

Solutions 1, 2, and 3 give the results of model allocations of the future growth to 1985 in three successive stages, including land values as a benefit (negative cost). The establishment cost breakdown shows the cost of each service on a per capita basis. The overall cost less benefit of establishment rises with time because the best sites are occupied early in the development period, leaving the least attractive sites to be developed last. The interaction costs and times do not appear to be significantly affected, although during the earlier part of the 15-year time period there is a slight decrease in travel costs and times because of a more efficient rearrangement of trip destinations. For these solutions, only 25 percent of the proposed 1985 freeway network was included. Greater economies are expected when larger portions of the network are included.

Figures 2, 3, and 4 show the growth over the three time periods as circles of activity. For easy visual comparison, the allocations are idealized as circles rather than dispersed.

Figure 5 shows the development pattern if the growth to the year 2000 is allocated simultaneously for a 30-year period. The average costs and travel times for this solution are the average over the 30-year period. The interaction costs and travel times are significantly higher than in the preceding solutions because of the greater dispersion of the low-density residential areas.

Solution 5 (Fig. 6) is a sensitivity analysis of the effect of constraining all future low-density development to 1985 to three satellites as shown. Even though the nonquantifiable benefits of decentralization have not been included, the increases in establishment and interaction costs over those in the other solutions for the same time period are not great. Hence, a satellite solution such as this (or some variation of this) is worthy of further investigation. The small additional costs and travel times may be weighed against the benefits of dispersion involved.

Other studies for sensitivity purposes that have been made, but that are not included here, are as follows:

1. Solution excluding land value as a benefit.
2. Solution with a different ratio of population increment split between high- and low-density residential activities.
3. Solution with establishment and/or interaction costs excluded.
4. Solution with population increment constrained to be equally split between the northwest and southeast sectors of the city.
5. Solution with a constraint that 25 percent of future industrial development to take place on edge of Westernport Bay (zone S2). This provides a means of testing the effect on the city if the proposed port development actually does take place.
6. Solutions for layouts optimized for individual service costs such as sewerage, water, and gas. These solutions may be presented to the individual service authorities to enable them to check the accuracy of the data they have provided.

CONCLUSIONS

The systems approach to urban planning provides a framework in which many factors affecting the future growth of our cities may be given due consideration.

An important part of this approach is to create or formulate a flexible structure whereby the model and the data may be continually refined as the study progresses and the general body of knowledge of urban modeling advances. This is facilitated by structuring the model into a hierarchy of modules or submodels that may be refined individually without producing premature obsolescence of the system model.

Figure 1. Urban system model.

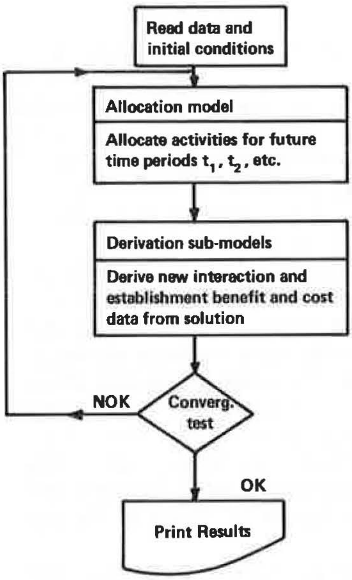


Figure 2. Model allocation for 1970-1975.

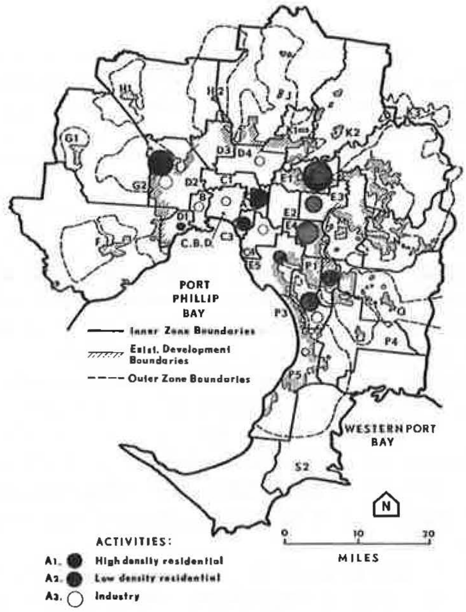


Table 1. Suboptimal solution for establishment cost breakdown.

Solution	Population Increase (percent)	Establishment Cost Breakdown (average cost per additional person in dollars)									
		Gas	Sewer-age	Water	Local Roads	Tele-phone	Drain-age	Schools	Elec-tricity	Land Value	Total
0 (1970 conditions)	–	–	–	–	–	–	–	–	–	–	–
1 (1970-1975)	17	67	285	160	680	280	133	370	490	-2,860	-400
2 (1975-1980)	33	73	298	180	710	295	122	368	600	-2,050	642
3 (1980-1985)	50	83	388	196	675	310	83	370	555	-1,700	960
4 (1970-2000)	100	84	641	236	690	310	114	368	528	-1,720	930
5 (satellite growth, 1970-1985)	50	91	410	420	760	320	175	370	500	-2,000	900

Table 2. Suboptimal solution for interaction cost breakdown.

Solution	Population Increase (percent)	Interaction Cost Breakdown (average cost per person per year in dollars)					
		Journey to Work	Industrial Trip	Residential Trip	Total	Public Transportation	Private Transportation
0 (1970 conditions)	–	167	77	58	302	78	224
1 (1970-1975)	17	167	73	55	295	76	219
2 (1975-1980)	33	167	73	55	295	72	223
3 (1980-1985)	50	172	75	56	303	69	234
4 (1970-2000)	100	206	85	59	350	72	278
5 (satellite growth, 1970-1985)	50	182	85	62	329	78	251

Table 3. Suboptimal solution for average travel times.

Solution	Population Increase (percent)	Average Travel Time (min)			
		Journey to Work	Industrial Trip	Residential Trip	Overall Average
0 (1970 conditions)	–	36.8	13.8	14.9	25.3
1 (1970-1975)	17	36.2	13.9	15.1	25.1
2 (1975-1980)	33	35.5	14.1	15.1	24.8
3 (1980-1985)	50	36.0	14.6	15.6	25.2
4 (1970-2000)	100	44.1	16.4	16.0	29.9
5 (satellite growth, 1970-1985)	50	38.8	16.0	15.8	27.2

Figure 3. Model allocation for 1975-1980.

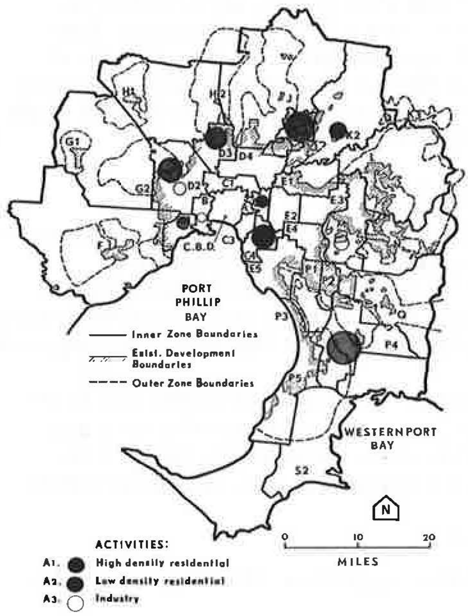


Figure 4. Model allocation for 1980-1985.

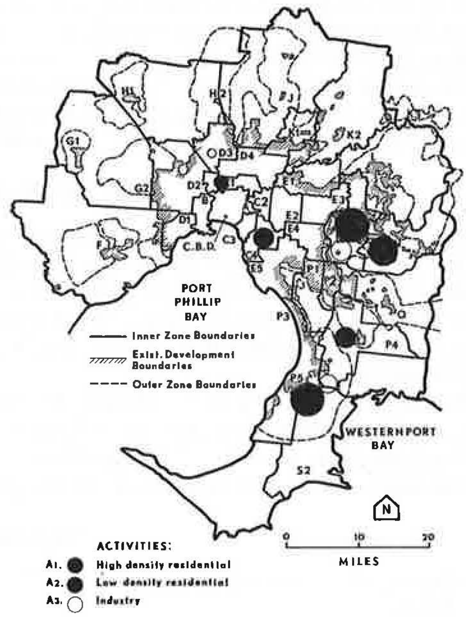


Figure 5. Model allocation for 1970-2000.

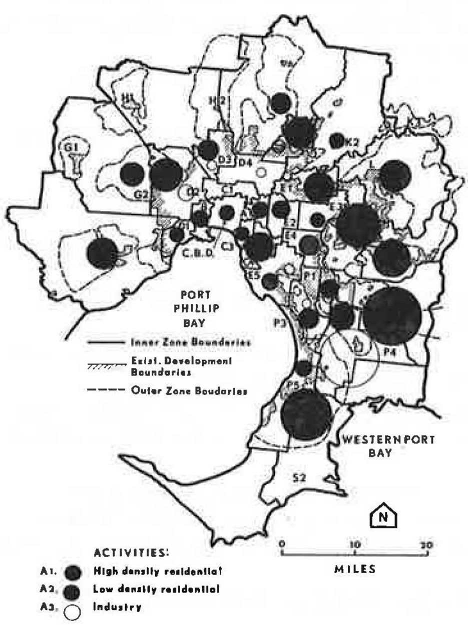
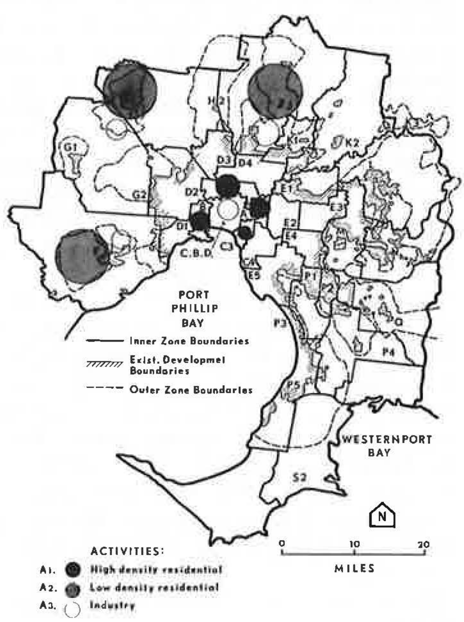


Figure 6. Sensitivity analysis, 1970-1985 (growth constrained to three satellites).



Likewise the study itself may be treated in a hierarchical fashion, where initial objectives are to determine what data are necessary and what macro layout patterns should be pursued in greater detail, e.g., satellite versus fringe development, thus enabling later stages of the study to concentrate on specific patterns of development.

The set of models developed is intended to form the basis of an information system for urban planning, allowing developer proposals to be analyzed, on a day-to-day basis, and long-term strategies for future growth to be tested and evaluated.

ACKNOWLEDGMENTS

The authors wish to thank the officers of the MMBW for the sponsorship of this study and for their constructive criticism in helping to synthesize the model and data.

The results and conclusions presented here are of an interim nature, being based at this time on incomplete data. They are presented primarily to show the methodology and are not to be taken as being the views held by the MMBW for the future development of Melbourne.

Thanks are also due to I. Abidin, P. Ahern, and D. Weinstock of CSIRO and to the officers of the many government authorities and private organizations who have supplied information and data for this study. The writers are particularly grateful to J. Paterson, economic consultant to the project, for his advice on benefits and costs.

REFERENCES

1. Owen, W. The Accessible City. The Brookings Institution, Washington, D.C., 1972.
2. Webber, M. On Strategies for Transport Planning. The Urban Transportation Planning Process, Organisation for Economic Co-operation and Development, Paris, 1971.
3. Dickey, J. W., Leone, P. A., and Schwarte, A. R. Use of TOPAZ for Generating Alternate Land Use Schemes. Highway Research Record 422, 1973, pp. 39-52.
4. Dickey, J. W., and Hopkins, J. W. Campus Building Arrangement Using TOPAZ. Transportation Research, Vol. 6, No. 1, March 1972.
5. Dickey, J. W., and Najafi, F. T. Regional Land Use Schemes Generated by TOPAZ. Regional Studies, to be published.
6. Dickey, J. W., and White, D. S. Hospital Design With TOPAZ. Proc., Internat. Congress of Cybernetics and Systems, Oxford, England, 1972.
7. Victorian Yearbook 1970. Commonwealth Bureau of Census and Statistics, Victorian Office, Melbourne, 1970.
8. Brotchie, J. F. A General Planning Model. Management Science, Vol. 16, No. 3, Nov. 1969, pp. 265-266.
9. Brotchie, J. F., Toakley, A. R., and Sharpe, R. On an Urban Planning Model. Tewksbury Symposium, Melbourne Univ., 1970.
10. Koopmans, T. C., and Beckmann, M. Assignment Problems and the Location of Economic Activities. Econometrica, Vol. 25, Jan. 1957, pp. 53-76.
11. Sharpe, R., Brotchie, J. F., Toakley, A. R., and Dickey, J. W. An Urban Systems Study of Melbourne. Presented to the Operations Research Society of America Meeting, Anaheim, Oct. 1971.
12. Ottosen, K. A. The Use of a Gravity Model to Analyse the Relation Between Homes and Workplaces in a Metropolitan Region. Proc., Urban Traffic Model Research Symposium, Planning and Transportation Research Corporation, London, June 1970.
13. Melbourne Transportation Committee. Melbourne Transportation Study. July 1969.