COMPUTER-AIDED SIMULATION SYSTEM FOR INTEGRATED LAND USE AND TRANSPORTATION PLANNING

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ABSTRACT

Changes in a transport system are likely to produce changes in land use pattern, and these effects are of considerable importance. Ultimately, progress in estimating such effects will depend on the development of a reliable model that embodies two- way interaction between transportation and land use. This paper presents an attempt to develop a computer-aided interactive system for integrated land use and transportation planning, on the basis of the simulation technique. The computer system developed in the scope of this study contains four modules: (a) an input data editor, (b) a land use-transportation model, (c) a graphic mapping module, and (d) a multicriteria evaluation program. The methodologies and the functions of this system are described in the paper, and an illustrative example that proves its capabilities is also provided.

INTRODUCTION

Solving urban transportation problems has long been a major objective of a wide range of transportation studies. Neither construction nor operational management can totally solve the transportation problems efficiently and economically. Urban transportation problems can be reduced only if a better understanding of the long-term interrelation- ship between land use and transportation is achieved [2]. Traditionally, such interrelationship can be investigated using transportation models within a specific planning process. The transportation models take the pattern of land use as given and predict from it how much traffic will be generated, which destinations it will go to, what modes it will choose, and which roads or rail lines it will use.

There are three main weaknesses in the traditional transportation planning process. First, the number of alternatives which can be generated from the planning process is often very limited. Second, the process produces large quantities of data that are hard to comprehend and interpret. The last and the most important weakness is the philosophy of the process itself, which takes land use as an exogenous input. Looking back on the history of the urban development, it is clear that not only the travel behaviour is dictated by the land use pattern, but the transportation systems have in their turn a profound effect on the land development [4].

For these reasons, a computer-aided planning model is needed to help in better understanding the complexities of an urban system, i.e. the two-way interaction between land use and transportation.

This paper presents an interactive graphic system, called SIMU, which is developed as a feasible tool for integrated land use and transportation planning. In the framework of a simulation procedure, SIMU predicts the amount of different land use activities to be allocated to each zone of an enormous metropolitan area. It guarantees finding a stable solution that optimizes the utilization of existing and proposed urban and transportation facilities under various development policies.

The paper begins with a brief description of the theoretical concepts embodied in the SIMU simulation system. Then its structural framework and the functionality of its different modules is illustrated. This is followed by an illustrative examples to demonstrate its efficiency and practical capabilities.

THEORETICAL CONCEPTS

General

The SIMU planning system is formulated on the premise that there is a bi-directional influence between land use and transportation. Land use activities generate travel demand, and in turn, the existence of new transportation facilities improve the accessibility and produces additional land demand for new activities at the locations served by these transportation facilities (Figure 1). This interaction is incorporated in the SIMU system by means of a simulation process consisting of a land use model and a transportation model.

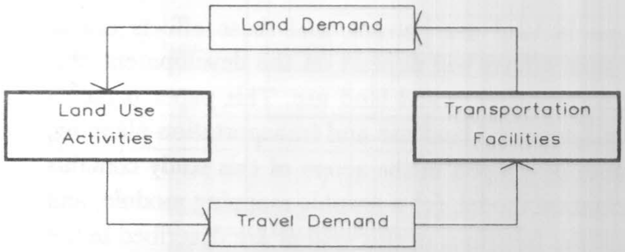


Figure 1. Interaction between transportation and land use planning

The land use model estimates firstly the activities needed for the study area, and allocates then the units of activities to each zone.

The transportation model investigates the effect of the generated land use plan on the proposed transportation system. It predicts the link volumes and travel times on the different links for both road and public transport networks. The model determines also the quality of service and the disutilities of the transport networks.

Land use model

The land use model is essentially an activity demand function coupled with an activity allocation algorithm.

The activity demand function is based on a Lowry-like model [9] for estimating the employment rates at each zone from the number of population projected by the planner. Employment can be categorized in some detail according to the type of activity (industry, trade, commerce, and service). The activity demand function has the following simple form [6]:

$$ER_{ik} = a_{ik} + (b_{ik} \, . \, \ln P_i)$$

where

ER_{ik} = Employment rate for activity type k in zone i (in %),

P_i = Population of zone i, and

a_{ik}, and b_{ik} are calibration factors obtained by regression analysis of the relationship between population and employment rate of activity type k in zone i.

The activity demand function produces a primary estimation concerning the number of active persons (employees and workers) generated from each zone. This estimation takes into account the specific population structure of that zone (age, sex, education, etc.). However, the resulting figures can be changed at any time by the planner, for example, to match the number of activities with the special urban characteristics of a particular zone (e.g. city centre, resort areas). Density constraint is also an important reason for altering the proposed locations of population and employment [12].

The SIMU planning system applies an optimizing model that uses mathematical programming to locate the different types of activities (work places) in a metropolitan area. It is based on the assumption that the land use activities should be located so that the sum of travel times for all home-to-work trips on the transport networks is minimized. If network capacities are initially ignored, this problem may be stated as a linear program. The general form of this activity allocation model can be expressed as follows:

$$\text{Min:} \quad \sum_i \sum_j \sum_k T_{ijk} \, . \, t_{ijk}$$

subject to the following constraints:

$$\sum_j T_{ijk} = E_{ik} \qquad (1)$$

$$\sum_i T_{ijk} = a_{jk} \, . \, X_{jk} \qquad (2)$$

$$X_{jk} = a_{jk} \, . \, X_k \qquad (3)$$

$$\sum_i E_{ik} = X_k \qquad (4)$$

$$T_{ijk} \geq 0 \qquad (5)$$

where

T_{ijk} = No. of trips from zone i to zone j for activity k,

t_{ijk} = travel time from zone i to zone j for activity type k,

E_{ik} = No. of active persons generated from zone i for activity type k
= $P_i \cdot ER_{ik}$,
A_{jk} = attraction factor of zone j for activity type k,
X_{jk} = amount of activity type k to be allocated to zone j, and
X_k = total activity k.

The objective function of this model is general minimum-time flow problem. It is simply the sum of trips on each link multiplied by the travel time of the link. The basic question in this formulation is to find the amount of activities (work places) to be located to each zone that minimizes the total travel time on the transport networks.

The principal constraint equations (Equation 1,2, and 3) are flow-balance relationships that ensure the balance of the results. Hereby, it is assumed that there is only one home-to- work trip per active person (at peak hour), and the sum of all active persons generated from all possible zones must equal the total number of work places allocated in the study area; i.e., the supply is identical to the demand (Equation 4). The last constraint equation (Equation 5) is clearly the non-negativity requirement that prohibits negative flows.

This simple linear program is solved in the SIMU system by the well-known Simplex method [10].

Transportation model

Since the land use model carries out the inter-zonal trip distribution, the transportation model bypasses the first two steps of the conventional transportation model (trip generation and trip distribution), and carries out only the modal split and the traffic assignment.

The transportation model serves for the equilibrium loading and travel times on a multi-modal network. The model is well suited to simulating the use of both road and public transport facilities, by defining link characteristics and the traffic flow classified according to trip purposes (O-D matrices).

The transportation model begins by building a set of short path trees from each origin to all destinations, using Dijkastra's algorithm [3].

Once the tree-building is completed, a modal split predicts the modal shares on each pair of zones for the different trip purposes. The modal split is a logit model, which depends on the values of the exponential of transport disutility [4]. The transport disutility is calculated as a function of travel cost and travel time, scaled by an elasticity factor, plus a discomfort constant for each mode. The mathematical expression is:

$$P_{ijm} = e^{-U_{ijm}} / (\Sigma e^{-U_{ijm}})$$

where

P_{ijm} = the proportion of traffic of mode m from zone i to zone j,
U_{ijm} = transport disutility, which may be stated as a linear function:

$$U_{ijm} = a_g (c_{ijm} + t_{ijm} \cdot tv_g) + d_{mg}$$

where

c_{ijm} = perceived cost for traveling from zone i to zone j by mode m,
t_{ijm} = travel time from zone i to zone j by mode m,
a_g = elasticity factor for population group g,
tv_g = time value for population group g (in L.E./hour), and
d_{mg} = perceived discomfort of mode m for population group g expressed in generalized costs.

The modal split algorithm is tested and the three parameters a, tv, and d are calibrated using actual data retrieved from the "Alexandria Traffic and Transportation Study", which was established on a comprehensive traffic survey and a household interview [11]. The test results are summarized in Table 1.

Table 1. Calibrated parameters of the modal split algorithm applied for Alexandria -test results-

population group (g)	a	tv	d_m				
			car	taxi	bus	tram	rail
car-owner	02.84	2.11	0.00	2.15	4.17	1.26	6.20
Non-car-owner	11.63	0.68	----	2.16	3.27	0.62	3.55

The final algorithm in the transportation model is an equilibrium traffic assignment, which is described and tested in other published paper [7]. This algorithm can be used to load the links of the multi-modal network with the modal traffic.

THE SIMU PLANNING SYSTEM

General

The construction of transportation models is still carried out by many planners using the established facilities of mainframe computers, which prove to be a headache in the majority of cases [1]. However good the programs are, only relatively superficial checks of model structure and of the sense of output are possible due to:

- the great amount of efforts required to set up a program run (programs generally require fixed format input, and file editing is very difficult under some operating systems),
- the large computing costs, and
- the lack of visual presentation (inspection of outputs and the plot of large numbers of maps by hand).

Therefore, the SIMU planning system is developed basically to overcome these problems, using interactive techniques and graphic displays wherever possible. In addition, SIMU has also two main features: (a) it is easy to use and easy to learn how to use, (b) it is capable of handling large networks. Limitations are felt to be about 12 000 links with 500 nodes. Note that these limits relate to the DOS computing system in which the program operates.

The programs which underlie the SIMU system are written in TURBO- PASCAL for the low-cost personal computers (IBM - PC/AT or equivalent), requiring no special equipment other than a mouse and EGA/VGA colour graphics. The programs can be run within 640 k of memory. A digitizer and plotter could be used to map out colour graphs.

System overview

Figure 2 presents the structural framework of SIMU. It is a computer planning system which embodies various modeling techniques (previously described).

Based on the inter-urban development plan (population distribution nation-wide), the land use model allocates the different types of activities (population and employment) to each zone of the study area. The allocation of activities depends on the inter-zonal accessibilities calculated from the travel times, as well as the inherent attributes of the zone itself. The interaction among the various employment activities and population can be controlled by the planner to satisfy desired intra-urban development policies (e.g, centralization and/or decentralization of activities and population growth).

The transportation model loads then the transport networks for the peak period, and predicts the service levels on each network link.

The results of the transportation model are entered again to the land use model, as they are variables for determining the locations of the land use activities. This simulation process is repeated until the resulting figures (location of land use activities, and link volumes) converge to an equilibrium state.

SIMU is designed to allow a planner to formulate and test a variety of ideas about the design of a city (alternative designs). It also allows the planner to change an existing land use pattern or to modify an existing transportation system (or to change both simultaneously). Then, it immediately calculates values for a set of criteria that is used to test how well the resulting land use/transportation alternative performs, in relation to other alternatives. SIMU supports a man-machine intuitively guided design process that consists of the generation and evaluation of a series of alternatives.

System functionality

SIMU is a menu-driven computer system. One of its important features is the removable, hierarchical menus which take the planner step-by-step through the planning process. The main menu contains options, each of which can be selected (using the computer mouse) to produce functional sub-menus. These sub-menus in turn may cause further menus to appear, from which another choice can be made.

Other main design feature of SIMU is the automatic saving of input data, graphs, and results on the computer disk. The stored data can optionally be displayed, plotted, or printed.

The SIMU planning system includes four individual modules: SIMU1, SIMU2, SIMU3, and SIMU4.

The SIMU1 module supports input data editing, such as project title, alternative number, land use pattern, and the characteristics of road and public transport networks. The SIMU1 has a build-in data checking function to help the planner to avoid and to correct input errors.

SIMU2 performs land use/transportation simulation. It uses an iterative technique that adjusts both land use and transport networks so that an equilibrium condition results

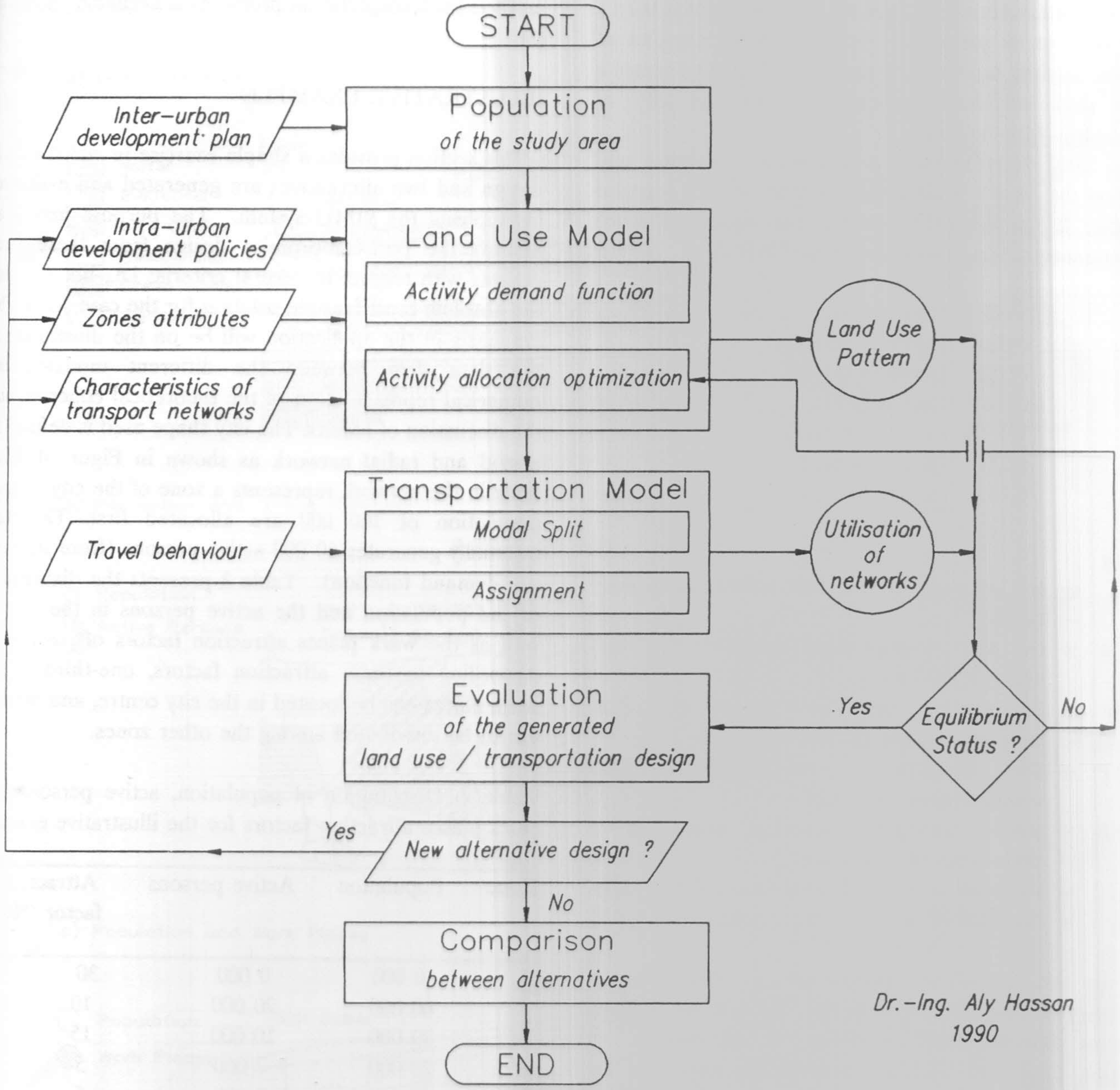


Figure 2. The structural framework of the SIMU planning system

from the computation. Congestion is the main link between land use and transportation models. If congestions are expected to rise, the design should be changed accordingly.

The SIMU3 module generates colour graphic displays using the input and output data from SIMU1 and SIMU2, such as land use pattern, network loading, and link congestions. Colour graphic displays enhances the evaluation process of the technical feasibility of alternative designs. SIMU3 employs the AUTOCAD - software to display graphs on the screen, and to draw them on a HEWLETT-PACKARD plotter or any hardcopy machine. It permits the planner to zoom and to map out windows of an original display at enlarged scale. In such manner, the planner can observe and modify the details of a limited subarea of a generated display. Thus, the planner can preview plots accurately before they are actually plotted. This is very beneficial for drawings which take a long time to be produced. Figure 3 shows samples of graphic displays produced by applying SIMU3 to create a basic land use/transportation plan for the city of Alexandria, as an example.

The SIMU4 performs a multicriteria evaluation and displays the results to help the planner identify superior designs. It automatically records the following seven performance criteria calculated from SIMU2:

V/C	(less is better)
PHSR	(more is better)
PHSP	(more is better)
COST	(less is better)
TRAN	(more is better)
OLL	(less is better)
ULL	(less is better)

where

V/C = the average of the link volume-to-capacity ratios

PHSR = the average peak hour speed on the road network (in km/h)

PHSP = the average peak hour speed of public transport system (in km/h)

COST = the investment costs (activities and transportation facilities)

TRAN = public transport ridership share as a percentage of total trips

OLL = the number of overloaded links (V/C > 1.0)

ULL = the number of underloaded links (V/C < 0.8)

While the first three criteria evaluate the technical efficiency of each alternative design, the next two criteria examine the economic feasibility of alternatives. In addition, OLL and ULL are nevertheless important for testing the disutilities of the transport networks proposed for each land use design.

The multicriteria evaluation is based on the concordance analysis [5]. This technique makes it possible to deal effectively with multiple, conflicting criteria that are always present in land use/transportation problems. Basically, concordance analysis involves the determination of the measurements and the relative importance weights of the evaluation criteria, and on this basis, it compares each alternative with all other alternatives. It produces the ranking of the alternatives and indicates those that are nondominated. The applying procedure of this evaluation method for transportation problems is available elsewhere [8].

ILLUSTRATIVE EXAMPLE

This section provides a simple exercise in which a basic design and two alternatives are generated and evaluated, by applying the SIMU system. The purpose here is to identify the best-compromise design from these three designs with respect to several criteria; i.e., not to select the absolute most feasible solution for the case study. The emphasis in the application will be on the illustration of the data flow between the different modules, the numerical representation of the theoretical concepts, and the discussion of results. The city shape used is defined by a grid and radial network as shown in Figure 4. Each node in the network represents a zone of the city. A total population of 160 000 are allocated first. This sum internally generates 60 000 active persons (from the land use demand function). Table 2 presents the distribution of the population and the active persons in the city, as well as the work places attraction factors of each zone. According to these attraction factors, one-third of the work places can be located in the city centre, and the rest are to be distributed among the other zones.

Table 2. Distribution of population, active persons, and work places attraction factors for the illustrative example

Zone	Population	Active persons	Attraction factor (%)
1	0 000	0 000	30
2	60 000	20 000	10
3	20 000	10 000	15
4	20 000	7 000	5
5	10 000	3 000	5
6	10 000	3 000	5
7	20 000	7 000	5
8	0 000	0 000	15
9	20 000	10 000	10
Total	160 000	60 000	100

The initial link capacity is set at 800 vehicle per hour (vph) for each grid and 1300 vph for each radial link. For

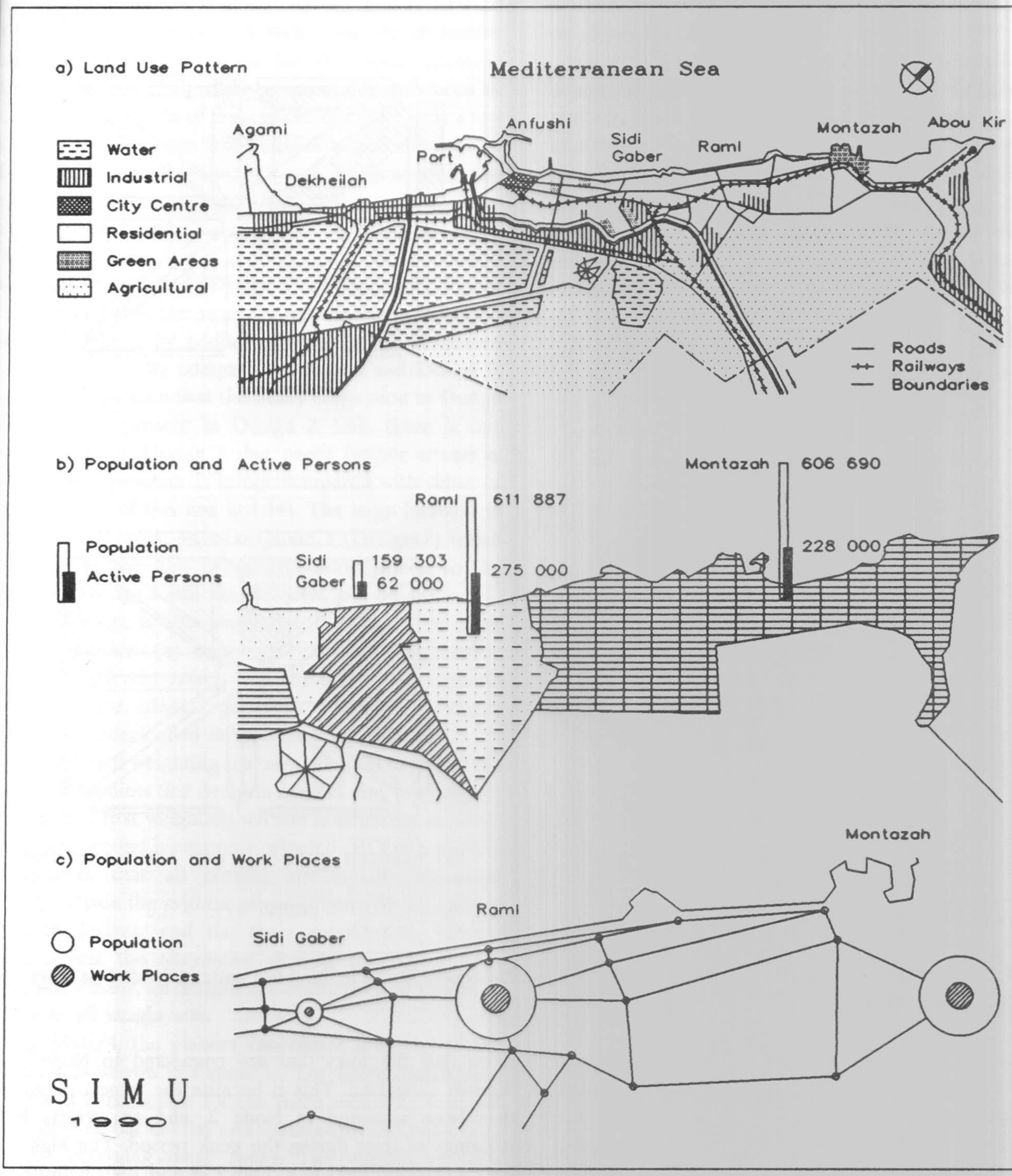


Figure 3. Image of the land use produced on a colour printer for the city of Alexandria -as an example-

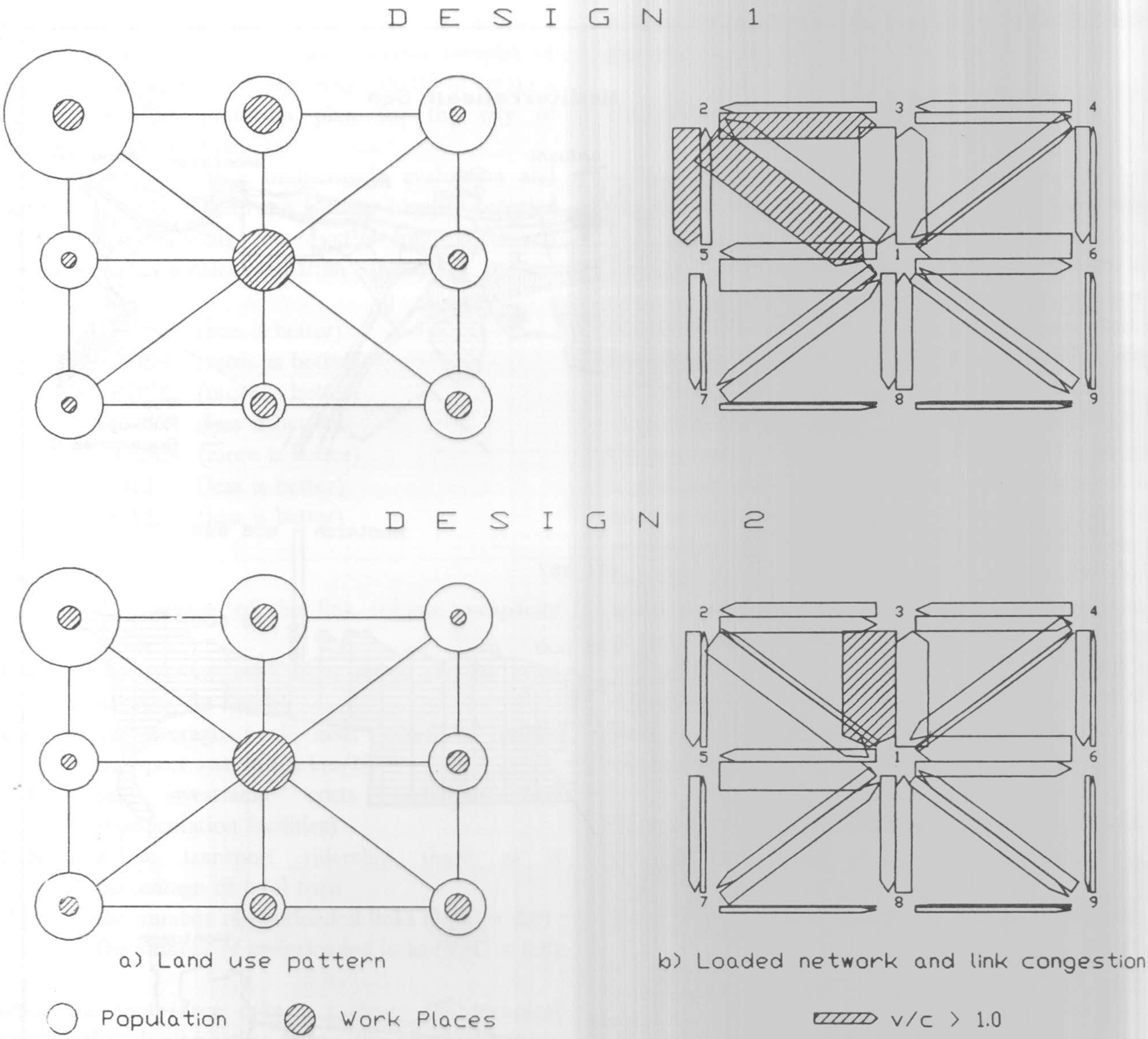


Figure 4. Comparison between Design 1 and Design 2 of the illustrative example; land use pattern, loaded network, and congested links

all internal links, a capacity of 2000 vph is used. In this exercise, it is also assumed that a public transport network (buses operating on mixed traffic) is evenly spread over the city. Each bus has a total capacity of 100 passengers, and is equivalent to 2.25 passenger car units.

Given these initial input data, the activity allocation model of SIMU2 produces the land use pattern shown in Figure 4 (Design 1). This Figure also illustrates the loaded network and the congested links. From this map it can be seen that the links that are connected to Node 2 are heavily congested. This is because the largest population has been allocated in Node 2, and so attracts heavy volumes of trips during the peak period. The high V/C ratios on these links (e.g. 1.40, 1.38 and 1.30) indicate that the link capacities are not well matched with the land use pattern of this area.

If the location of population and work places are kept fixed, one way to relieve the heavy congestion is to increase capacities of certain links. Solving this problem involves determining how much capacity to add to each link, and where to do that. A wide range of alternative designs can be created even for this small network. Moreover, billions of alternatives can also be produced by changing the allocation of population. In reality, only a few number of these designs will be efficient and economical. However, the more alternatives can be generated and evaluated, the more probable it is, that a truly superior solution will be found.

For the purpose of this exercise, only two alternative designs are investigated (Design 2 and Design 3). Figure 4 (Design 2) shows the land use pattern, and the loaded network produced by adding capacity to the congested links in Design 1. By comparing Design 1 and Design 2, it can be quickly seen that the heavy congestion in Design 1 is no longer present in Design 2. Still, there is one congested link in Design 2 that needs further attention. However, this problem is minor compared with those of Design 1 (V/C of this link is 1.14). The large increase in population and work places at Node 3 (Design 2) which resulted from the link capacity additions made to the network of Design 1 can also be seen.

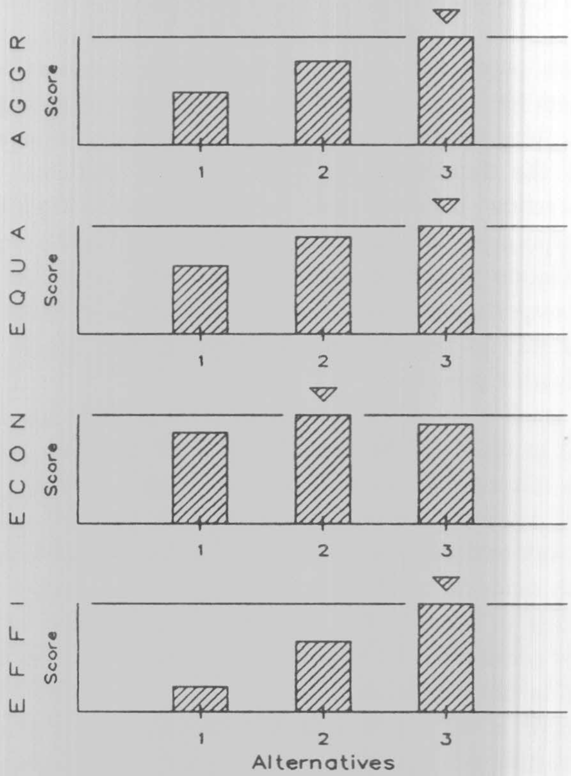
A third Design is also generated. It is based on other land use policies: (a) equal distribution of population among the different zones, and (b) unique work places attraction factor. SIMU2 produces a transport network with almost underloaded links, i.e. no congestions.

Three different weighting schemes are used to reflect the different viewpoints that decision makers may bring to this problem. The first weighting scheme is efficiency oriented (EFFI), the second is economy oriented (ECON), and the last assumes that all criteria are equally important (EQUA). Given the criteria values (Figure 5) for each of the three designs, and the three weight sets, SIMU4 evaluates first the alternative designs relative to each weight set. Finally, all designs are evaluated and ranked in relation to all weight sets.

Using SIMU4, the planner can obtain a display of the evaluation as shown in Figure 5. The display introduces the rank of each design for the three weighting schemes in the form of bar charts, and underneath the input data used for obtaining these ranks. The weights of each evaluation criterion are aggregated and averaged to produce the final ranking (AGGR) that shows the best-compromise design (Design 3) on the top of the display.

Ideally, the design which is ranked highest and is nondominated for every weighting scheme is the best one. However, in many cases, this result is not easily achieved and a more detailed examination of the sensitivities of the weighting is necessary.

None of the designs is totally nondominated for all weighting schemes. Design 3 is ranked highest (final ranking). Although Design 3 is the second most costly alternative (weighting scheme 2), it produces better benefits for the other criteria than the other designs do. This means, that Design 3 is dominant using only the cost-oriented weighting scheme. If the weight on cost is moved down to as little as 9, Design 2 will be dominated by Design 3, which costs considerably less.



	V/C	PHSR	COSTS	OLL	ULL
1	0.57	32.26	1280	3	10
2	0.46	35.35	1731	2	8
3	033	44.12	2206	0	32
EFFI	10	8	2	6	4
ECON	5	5	10	2	2

Figure 5. Display of the multicriteria evaluation for the illustrative example

This is an example of the type of trade-off information that can be obtained from the evaluation display.

Hereabout, it should be emphasized that it is not suggested that the results from SIMU4 are to be accepted as it is and used alone for decision making. The results simply represent an objective comparison for use in a decision-making process. Before a final decision is reached, such results need to be carefully examined. SIMU4 has been designed to support an effective evaluation process and to help the planner more clearly to identify the significant differences among alternative designs.

CONCLUSIONS

This paper has presented the SIMU computer-aided system for integrated land use-transportation planning, by describing the theoretical basis, the structural framework and the functionality of its different modules. The interaction between land use and transportation is incorporated in the SIMU system by means of a simulation procedure consisting of a land use model and a transportation model. Both models are linked together in a way to support an interactive graphic design and evaluation process.

A small-scale land use-transportation problem has been used to illustrate the capabilities of the planning system with reference to three alternative designs. Several maps were developed to display the land use pattern and the network performance of each design. The congestions are easily detected on these maps. Concordance analysis was applied to identify the best-compromise design of the three considered. Three different weighting schemes were used in the evaluation.

There is no doubt that the provision of a graphic interactive technique to a land use/transportation planning system brings many benefits. A better understanding of the planning phases is possible, productivity in terms of the number of alternative designs to be generated and evaluated is increased, and higher- quality results are attainable. In addition, visual display of graphs increases the accuracy and greatly reduces the time needed for the planning process.

For practicing professionals, the SIMU planning system may be a powerful and effective approach that deals effectively with complicated land use/transportation problems in enormous metropolitan areas.

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