CAPACITY EXPANSION MODELING OF WATER SUPPLY IN A PLANNING SUPPORT SYSTEM FOR URBAN GROWTH MANAGEMENT

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도시성장관리를 위한 계획지원체계에서 상수도의 시설확장 모델링

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ABSTRACT

A planning support system enhances our ability to use water capacity expansion as an urban growth management strategy. This paper reports the development of capacity expansion modeling of water supply as part of the continuing development of such a planning support system (PEGASUS: Planning Environment for Generation and Analysis of Spatial Urban Systems) to incorporate water supply. This system is designed from the understanding that land use and development drive the demand for infrastructure and infrastructure can have a significant influence on the ways in which land is developed and used. Capacity expansion problems of water supply can be solved in two ways: 1) optimal control theory, and 2) mixed integer nonlinear programming (MINLP). Each method has its strengths and weaknesses. In this study the MINLP approach is used because of its strength of

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determining expansion sizing and timing simultaneously. A dynamic network optimization model and a water-distribution network analysis model can address the dynamic interdependence between water planning and land use planning. While the water-distribution network analysis model evaluates the performance of generated networks over time, the dynamic optimization model chooses alternatives to meet expanding water needs. In addition, the user and capacity expansion modeling-to-generate-alternatives (MGA) can generate alternatives. A cost benefit analysis module using a normalization technique helps in choosing the most economical among those alternatives. GIS provide a tool for estimating the volume of demanded water and showing results of the capacity expansion model.

요 약

계획지원체계는 도시성장관리수단으로 간선시설 시설확장을 이용하는 우리의 능력을 증진시킨다. 이연구는 그러한 계획지원체계 (PEGASUS: 공간도시체계의 생성 및 분석을 위한 계획환경)의 개발계획의 일환으로서 상수도 시설확장모델의 개발에 관한 연구이다. 이 연구는 토지이용과 개발은 간선시설의 수요를 유발하고 간선시설은 토지가 이용되고 개발되는 방향에 영향을 미친다는 전제하에서 시작된다. 상수도 시설 확장은 2 방법으로 해결될 수 있다: 1) 최적통제이론, 2) MINLP 방법. 이 방법들은 각각 장단점을 가지고 있다. 이 연구에서는 동적 시설 확장 크기 및 시기를 동시에 결정할 수 있는 MINLP방법이 채택이 되었다. 상수도 관망해석모델과 동적 상수도 시설 최적화 모델이 상수도계획과 토지이용계획의 동적 연관관계를 해결할 수 있다. 상수도 관망해석모델은 생성된 관경의 적정성을 분석하며 동적 상수도 시설 최적화모델은 변화하는 상수도 수요량을 충족할 수 있는 대안을 작성한다. 표준화기법에 의한 비용편익분석은 가장 경제적인 대안을 선정한다. GIS는 필요 상수도 수요량을 산정하고 시설확장모델의 결과를 이용자에게 보여주는데 훌륭한 역활을 할 수 있다.

Geographic Information Systems (GIS) are a powerful tool for collecting, sorting, retrieving, transforming, and displaying spatial data in connection with attribute data. However, GIS lack analytical modeling capabilities (Densham and Goodchild 1989) and graphic interface functions (Walsh 1993), especially in dealing with dynamic planning problems. Decision Support Systems (DSS, Silver 1991; Davis-Stemp et al. 1986; Sprague and Carlson 1982; Sprague 1980; Keen and Morton 1978) provide user interface and modeling functions. DSS make up for the limitations of GIS. Spatial Decision Support Systems (SDSS), a new class of DSS, result from the melding together of GIS and DSS (Walsh 1993). SDSS provide users with a unifying framework for integrating the capabilities of GIS and DSS in making a decision with respect to problems that have spatial dimensions. The functions of GIS such as map display functions, primary analysis functions, and spatial and nonspatial data manipulation functions are coupled with the functions of DSS such as graphic user interface, models, and databases. Planning Support Systems (PSS, Harris and Batty 1993; Harris 1989) add more advanced spatial analysis functions than GIS and intertemporal functions to the functions of SDSS. We focus on capacity expansion of water supply rather than the usual focus on transportation. A PSS for capacity expansion model of water supply (PSS/CEWS) seeks to find the capacity of a set of water-distribution networks to meet changing water demand and to manage urban growth. This paper reports our progress toward an operational PSS that addresses various infrastructure investment questions related to urban growth.

CAPACITY EXPANSION MODELING OF WATER SUPPLY

Capacity expansion problems of water supply can be solved in two ways: 1) optimal control theory (Intriligator 1971, pp.344-369;

Wymer 1994; Chang 1992, pp.159~314), and 2) mixed integer nonlinear programming (MINLP, Brooke et al. 1992). The first, capacity expansion modeling using optimal control theory, determines capacity expansion through simulation of state equations, predefinition of lumpy projects, the static network optimization model, the network analysis model, the capacity expansion model using optimal control theory, and capacity expansion MGA using Hop, Skip, and Jump (HSJ) method. The second, capacity expansion modeling using MINLP, consists of the dynamic water-distribution network optimization model, the network analysis model, and capacity expansion MGA manipulating model parameters. Each method has its strengths and weaknesses. The first method incorporates price effects on demand but relies on predefined networks for each expansion . The second method chooses networks and expansion timing simultaneously, but does not incorporate effects of price on demand.

Capacity Expansion of Water Supply

The capacity expansion modeling provides information about how to expand the water-distribution networks so that they meet increasing demand over time. This involves deciding the expansion size (sizing), expansion times (timing), expansion location, and expansion types (Luss 1982). The design period of water networks (i.e. the length of time from capacity construction to full use of capacity) depends on the discount rate, projected demand, construction and management costs, and the ease of capacity expansion. We make the following assumptions pertinent to the installation of water capacity over time in order to simplify the dynamic capacity expansion model:

(1) Capacity is durable; that is, capacity once installed has an infinite life.

(2) Consumption cannot exceed capacity.

(3) Negative demand increments are not allowed.

(4) Demand is deterministically forecasted.

(5) There are no holding costs for excess capacity.

(6) The addition of capacity to existing capacity is additive.

(7) There are no lag times from decision to service provision; that is, no construction time.

Method 1: Capacity Expansion Modeling using Optimal Control Theory

Capacity expansion modeling of water supply using optimal control theory is composed of five major parts (Figure 1). The first is Supply. In this step, a virtual water-distribution network, which includes all possible links, is generated based on street network. The second is Demand. In this step, we calculate the amount of water demanded per parcel and aggregate this demand to nodes on a water-distribution network using GIS. The third is Network Modeling. Water-distribution network alternatives for given levels of water demand are identified by the user, by using modeling-to-generate-alternatives (MGA) (Hopkins, Brill, and Wong 1982; Brill 1979), or by a network optimization model. The fourth is Capacity Expansion. A capacity expansion model generates capacity expansion alternatives that sequence and choose the timing of network projects to meet changing demand. The fifth is Evaluation. Economic evaluation models using a normalization technique (Mishan 1988; 1982) help to choose among alternatives. A water-distribution network optimization model (Brooke et al 1985), a network analysis model (Cross 1936), and a capacity expansion model are linked to a GIS, which in this study was ARC/INFO (ESRI 1992).

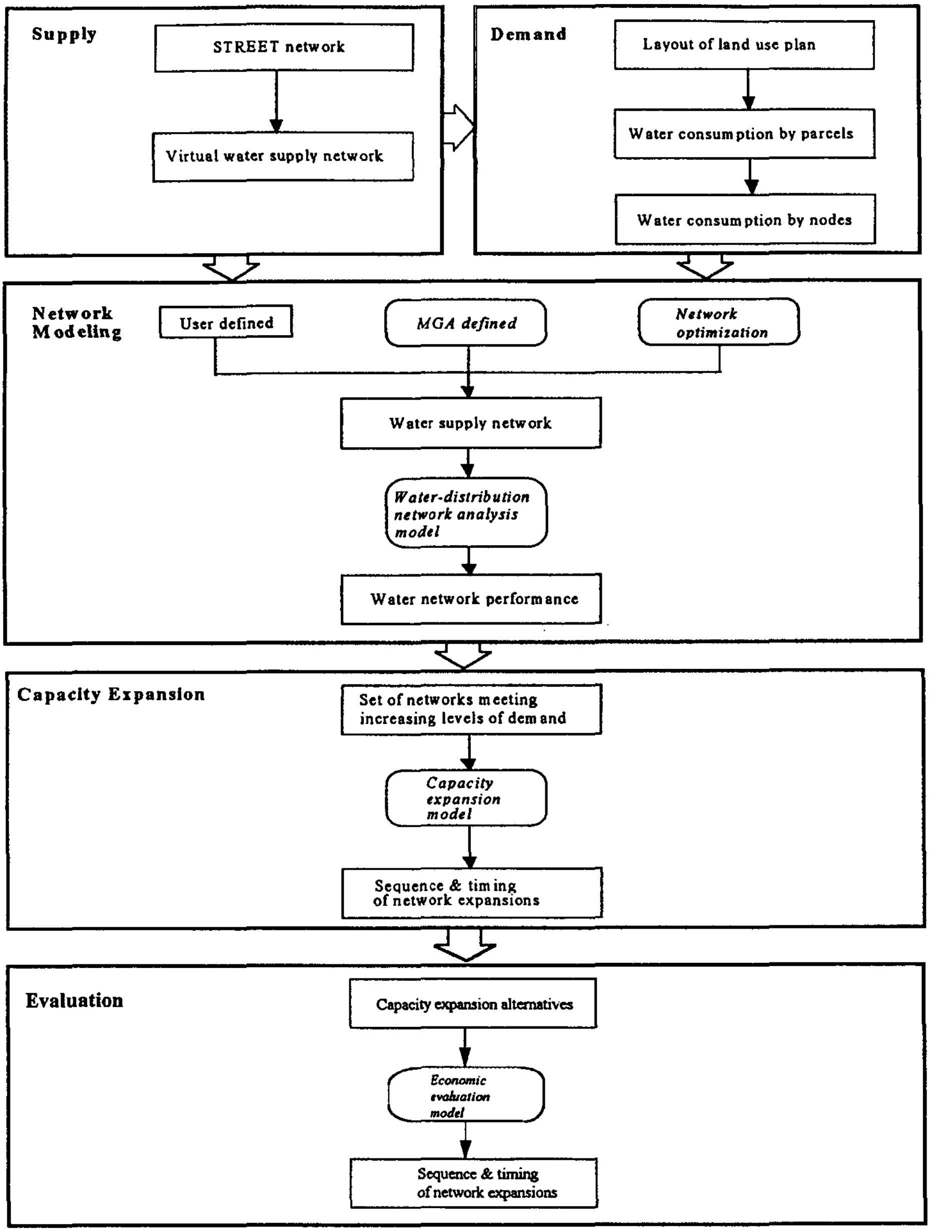

Figure 1. Design of PSS/CEWS Based on Method 1

Method 2: Capacity Expansion Modeling Using MINLP

One behavioral simplification in the capacity expansion modeling using MINLP is that water demand increases exogenously and independently of capacity expansion decision. In particular, pricing effects are not considered. Capacity expansion by the dynamic water-distribution network optimization model using a mixed integer nonlinear programming includes three advantages over capacity expansion using optimal control theory: 1) finds expansion alternatives including future capacity expansion times, sizes, locations, and pipe types of a water-distribution network provided, 2) has the capabilities to do the capacity expansion of each link spatially and intertemporally, and 3) requires less interaction between models.

PSS/CEWS using MINLP is composed of four major parts (Figure 2). The first is Supply. In this step, a virtual water-distribution network, which includes all possible links, is generated based on a street network. Initial networks defined by the user are generated based on the virtual network. The second is Demand. In this step, we calculate the population to be served and the amount of water demanded per parcel and aggregate this population and demand to nearest nodes on a water-distribution network using GIS. The third is Alternative Generation. Water-distribution network alternatives for given levels of water demand over time are identified by the dynamic network optimization model, by the user, and by using capacity expansion MGA (Dickey, Leone, and Schwarte 1973). The user can edit pipe sizes of alternatives until they are satisfactory to the user and they meet the design criteria. The fourth is Evaluation. Economic evaluation models using a normalization technique help to choose among alternatives.

Demand requires initial nodes defined by the user from Supply. The pipe sizes of water-distribution networks are calculated to meet the demand over time under the assumption that population increases in the study area, depending on the pattern of development and land use change. The size and construction costs of generated networks are transferred to the water-distribution network analysis model to obtain better estimates of network performance. If the result shows that water pressures at some nodes do not meet design criterion, some pipe sizes near the corresponding nodes should be changed and the network analysis model repeated.

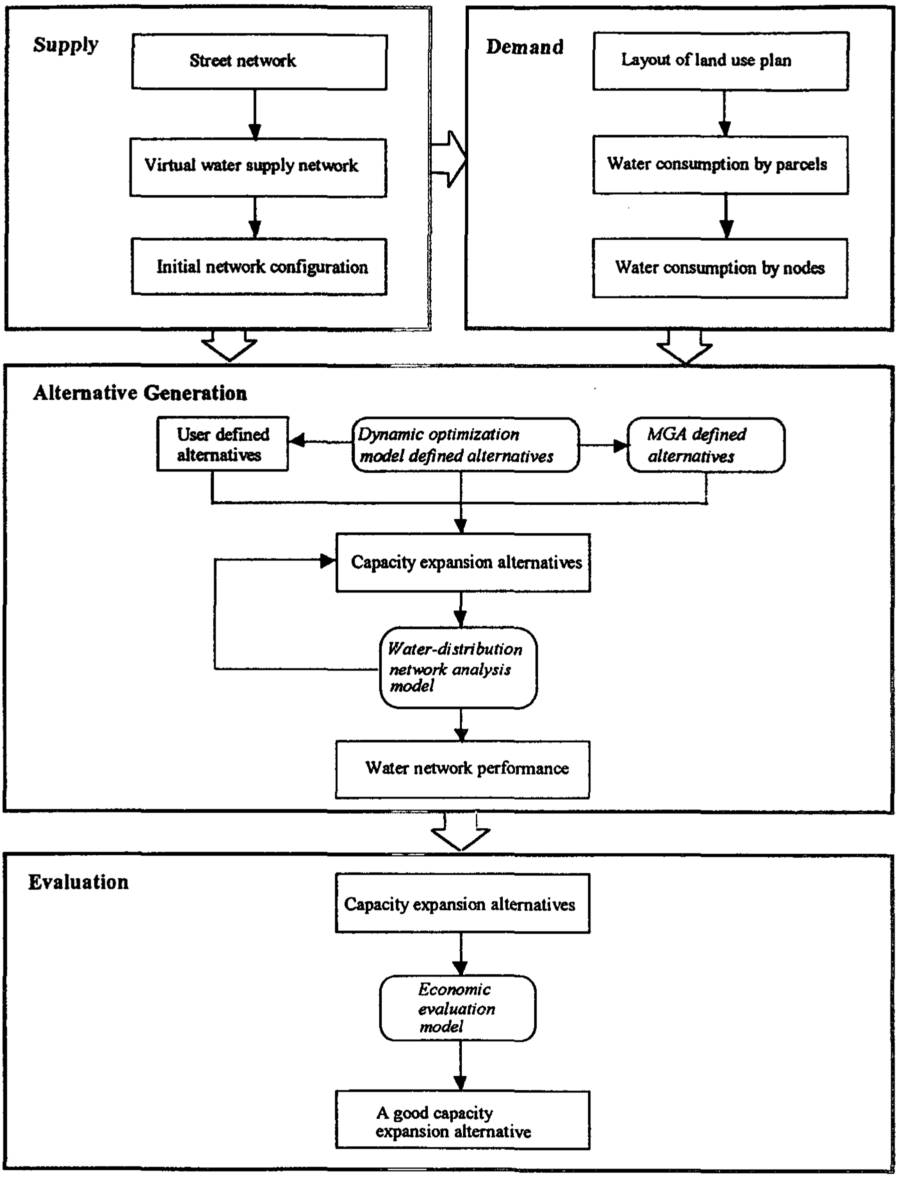

Figure 2. Design of PSS/CEWS Based on Method 2

DEMONSTRATION APPLICATION

The two cases as scenarios in this study are 1) redevelopment of an existing urban area, and 2) new development for a variety of land uses. PSS/CEWS enables the user to obtain the answers to the questions raised in the planning process of each scenario.

CONCLUSIONS

PSS/CEWS provides the user with several tools: 1) aggregating water consumption by nodes and generating a virtual water network and initial water networks using GIS; 2) identifying water-distribution network alternatives by user definition, the dynamic optimization model, or MGA; 3) evaluating the performance of water networks using the network analysis model; 4) choosing an alternative among alternatives using a normalization technique; and 5) showing results of capacity expansion model using GIS.

Capacity expansion modeling using optimal control theory has a big advantage of figuring out the dynamic relationship between cost, price, and demand, which capacity expansion modeling using MINLP does not. However, this approach using optimal control theory in the capacity expansion of water supply is up against several limitations: 1) too much interdependence between capacity expansion and network analysis models as discussed in the above, 2) too many assumptions in capacity expansion modeling, 3) difficulties in determining capacity expansion location in a water-distribution network, 4) theoretical and practical difficulties of applying optimal control theory capacity expansion requiring jumps in the state variables, and 5) determination of only timing of predefined lumpy projects. In addition to these limitations, since every state variable is influenced by an exogenous variable, the necessity of optimal control theory diminishes.

MINLP approach, in which an existing static water-distribution network optimization model is extended to include time, can make up for the five limitations of the optimal control approach. Though MINLP approach fails in controlling variables and addressing the dynamic relationship between cost, price, and demand, it can determine sizing, timing, locations, and types of capacity expansion in a water-distribution network. MINLP approach can be justified in a rather small area in which water price is determined administratively. Combining optimal control theory and MINLP in the capacity expansion of water supply can make up for counterparts limitations and make it possible for planners and engineers to generate capacity expansion alternatives in consideration of the relationship between cost, price, and demand.

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