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Mixed integer linear programming approaches for land use planning that limit urban sprawl

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ABSTRACT

Sprawl has a detrimental effect on quality of life and the environment. With dwindling resources and increasing populations, we must manage sprawl. Ewing et al. (2000) defined factors to measure sprawl in the present urban structure. The measures are divided into four broad categories, which are density factors, mixed use factors, street factors, and center factors, and can be used in future planning of metro areas. In this research, we develop a mixed integer programming model to optimize land usage subject to sprawl constraints, which are based upon the aforementioned sprawl measures. Due to the large size of the problem, we employ a combination of heuristics and Benders' decomposition similar to one described by Bazaraa and Sherali (1982) to provide an urban planner with suitable land use assignments. We show examples demonstrating how the planner can use this approach to analyze how various factors that affect land use and sprawl measures. Finally, we discuss topics of future research.

1. Introduction

With the industrial revolution, raw materials and finished products were needed to be delivered to the factories and to market areas. Thus, the cities needed streets, railways, shipping lanes without which the industrial revolution would have been impossible. Increased commerce and manufacturing led to congestion, new safety hazards, and air and water pollution. As the central areas became more crowded, the wealthy began moving into the suburbs. The invention of the automobile only served to hasten and promote this migration. This phenomenon was marked as an early form of urban sprawl.

1.1. Overview of urban planning and methods

According to Catanese and Snyder (1979), the earliest known examples of urban planning were by the Sumerians of Assyria. Their cities included fortresses and marketplaces for populations of 3000–5000 people that lived in them. The common characteristic among all of the ancient cities was that they were all built along great rivers, which afforded various advantages with regards to transportation and defense.

The first example of zoning in cities was in the first century A.D. in Rome when Augustus established a 70-foot height limit. Rome struggled with the problems of overcrowding and transportation when its estimated population grew from 250,000 to 2,000,000 residents. To mitigate these problems, Romans started building roads and military cities. All of these developments in the ancient world established a pattern in which cities are now built. There are four layers in the pattern. The first one is a *physical base*, which is the visible form of the city, like the roads, buildings, and parks. This was illustrated by the rectangular pattern of the street systems. The second layer is the *political base*. For example, ancient cities were built around fortresses where the rulers of the land resided. The third layer is the *economic base*, where the planner locates various centers of commerce in the city, such as the marketplaces. The fourth layer is the *social base*, where the planner allows for open spaces or centers where the residents may assemble and socialize.

According to Catanese and Snyder (1979), the major components for the urban planning process are problem diagnosis, goal articulation, prediction and projection, alternative development, feasibility analysis, evaluation, and implementation. In *problem diagnosis*, a planner must identify which problems afflict the present city, and then, define them in specific terms. However, the problem diagnosis depends on the individual planner's perspective on definitions of various norms, ideologies, and standards. Descriptive statistics is used extensively to describe a problem, such as means, medians, ranges, and ratios. An important source of information at this stage for the planner is the U.S. Bureau of Census. If the data needed by the planner are unavailable, then he/she must use survey research methods to generate specific

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information. After identifying the problems, specific goals must be set as to what extent the problem has to be resolved. The challenge lies in translating the verbal goals into operational objectives. The planner must determine the time span of the project. Future projections of the population growth and trade are required, since they have a direct effect on the services in the city.

After that the planner develops alternatives to the original plans. If the situation is simple, the planner has already been given a location and does not have many competing factors. But if the situation is complex and involves many different aspects, then the planner must develop multiple options. Even though the model inherently accounts for constraints, such as the size and availability of land and finance, the planner must also ask whether the alternatives are feasible on other vague constraints, such as organizational or political acceptability. As early as 1912, planners drew maps by hands of various topographical features of the land. These maps were then combined together to recommend changes in land use. This posed a problem since there was a limit to what may be feasible by hand.

One of the first places to use computers to help draw overlay maps was in Harvard in 1963. The trend continued to surge as computers became more powerful and the techniques to draw the maps became more sophisticated. The spatial data, which describe the various attributes of the land in quantifiable terms, were used as an input to optimization models. Since there are conflicting objectives when planning a city, researchers introduced decision making models where multiple criteria were evaluated. Moreno and Seigel (1988) provides an application of multiple criteria evaluation via an impact analysis for the building of a highway corridor in Colorado. We examine land-use suitability analysis, which is a tool that identifies the most suitable places for locating future land uses (Collins et al., 2001).

1.2. Overview of sprawl

As we have seen from the history of urban planning, the rise of sprawl as an issue has its roots in the Industrial Revolution. There is no consensus in the literature as to the definition of sprawl. It goes to show how difficult it is to try to measure sprawl quantitatively. There are some characteristics that are common among the many attempts to define sprawl in the literature. Those are unplanned and scattered development, low population density, high reliance on automobiles, and locations outside of the metro area. In this paper, we primarily concentrate on sprawl in the context of the United States. Delafons (1962) attributes the U.S. system of urban planning to be influenced by "prairie psychology". Traditionally, development in the U.S. assumes a virtually unlimited supply of land, that land is accessible to everyone and the rights of ownership are protected by the U.S. Constitution, market driven growth is not intervened, planners do not question the need for development, and an inherent distrust towards the government and minimal public review of the policies that are already in place.

All of these social and institutional factors combined to aid urban sprawl. There are many reasons why sprawl is a cause of concern. The pace of development in the U.S. has not been proportional to the rate of population growth. For example, in the metropolitan area of Cleveland, the amount of developed area increased whereas the population decreased (Benfield et al., 1999). Loss of open space is a major contributor in prime farmland being lost to development. Low density and discontinuous development make automobile use mandatory, which results in increased usage of vehicles degrading air quality, and drivers spending on average 51 h per year stuck in traffic (Howlett, 2003). Clearing land for highways, residential areas, and service areas due to sprawl lead to the destruction of green cover, which causes climate change. Sprawl leads to the destruction of the wetlands and forests, and hence, it impedes nature's ability to provide clean water.

With all of the issues surrounding sprawl, there have been past attempts to estimate the costs associated with it. One of the more significant studies done on the costs of sprawl was by Burchell (1998, 2002). Burchell (1998, 2002) divided the costs into five major categories: public and private capital and operating costs, transportation and travel costs, land/natural habitat preservation, quality of life, and social issues. All of the negative impacts of sprawl motivate the development of tools assisting urban planners in designing cities/downtowns that would be walk-able and transit oriented. In our research, we develop a mixed integer linear programming (MILP) model that limits the negative effects of sprawl by managing various parameters that were derived from the Transportation Research Board report by Ewing et al. (2002).

The remainder of this paper is organized as follows. In Section 2, we describe related literature and the contribution of this research. Section 3 presents the MILP formulation, including a problem description, assumptions, sets, variables, and the model justification. In Section 4, we develop a Benders' decomposition algorithm to solve the MILP. In Section 5, we present an experimental set up and results. Finally, in Section 6, we discuss conclusions and future research.

2. Literature review and contribution

In this section, we discuss literature of land use optimization, which includes linear and integer programming techniques. Afterward, we discuss literature on measurement and optimization of sprawl, decomposition methods, and the quadratic assignment problem. Finally, we discuss the contribution of this research.

2.1. Land use optimization

Most literature on land use optimization models consider at least one aspect that affect sprawl. These considerations include managing peak run off, air quality, and traveling costs. The term that is frequently associated with sustainable land-use planning is smart growth. *Smart growth* refers to judicious stewardship of natural resources to prevent urban sprawl. To differentiate between the literature of simple land use allocation and sprawl, literature that explicitly mentions sprawl or sustainability as an objective are discussed in Section 2.2, while other literature on land use allocation are described in this section.

GIS-based land use suitability analysis has been used to solve an array of problems. For example, it has been used in ecological models for defining land suitability (in this case, habitat for animal and plant species (Pereira and Duckstein, 1993; Store and Kangas, 2001), geological preference (Bonham-Carter, 1994), suitability of land for agricultural use (Cambell et al., 1992; Kalogirou, 2002), environmental impact evaluation (Moreno and Seigel, 1988), site selection for facilities location (Church, 2002; Eastman, 1993), and regional planning (Janssen and Rietveld, 1990)). There is also a significant part of the literature that is concerned with simultaneous optimization of land use assignment and transportation with the focus on minimizing traveling cost (Los, 1978; Moore and Gordon, 1990; Ouyang and Lam, 2009; Vold, 2005). Moore and Kim (1995) extend the integration of land use and transportation to include environmental applications as well. Another area of research is on optimizing the land use allocation problem with respect to economic activities (Beckmann, 1956; Koopmans and Beckmann, 1957; Mills, 1972; Moore and Gordon, 1990). Increasing popularity of sustainability has led to research focusing on sustainable spatial optimization of land use allocation (Ligmann-Zielinska et al., 2005; Ward et al., 1999, 2003). All of the papers cited above account for only some sprawl measures.

Most literature on land use allocation uses integer programming (IP). The decision variable of these IP models determine whether a