A Heuristic Method for Land-Use Plan Generation in Planning Support Systems

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Abstract: Existing land-use allocation methods assume that the suitability of a spatial distribution of land-uses can be measured as the sum of suitability scores across parcels. Although this may be plausible for some land-uses, facilities such as retailing, schools, medical services, etc., intend to serve the needs of a local population and should be evaluated at the level of a facility network, instead. The purpose of the present paper is to develop a method that combines a suitable heuristic for facility-location planning with an existing mechanism for land-use allocation, to solve this shortcoming of existing models. In specific, the proposed method combines the interchange heuristic for locating facilities and a swapping heuristic for area-type land-use allocation in a multi-agent framework. A case study shows that the method generates plausible land-use plans in reasonable computation time.

1. INTRODUCTION

Land-use plans provide local authorities with an instrument to control or influence new developments in existing or new urban areas within the boundaries of their jurisdiction. Supporting the generation of land-use plans is a long-standing aim in spatial model and system development. In this paper, we consider the well-known problem of determining the spatial allocation of land-uses given the boundaries of a plan area, a classification of land-uses and the task size of each land-use (where *task size* denotes the total area to be realized of the land-use). Existing methods dealing with this land-

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use allocation problem have proven their value either in models for predicting land-use changes over time (descriptive, e.g., White and Engelen 1993) or for supporting plan decisions (prescriptive, e.g., Klosterman 1999). The suitability functions used may differ in important respects between approaches. However, invariably and implicitly the functions are based on an assumption that may not hold for every type of land-use. That is, they assume that the suitability of a spatial pattern of a certain land-use is equal to the sum of the suitability scores across the spatial units of that land-use. This assumption may be valid or good enough an approximation for area-type land-uses such as, for example, housing, industry and agriculture, but is problematic for land-uses that correspond to services for a spatially distributed demand, such as, for example, retail centres, schools, green parks and medical services. In the latter case, the spatial units of the land-use constitute a network of facilities and suitability should be evaluated at the level of the network. For example, a location that has a low suitability score when considered individually may still be part of the best possible network for the facility. From the network point of view, every location is as suitable as the performance of the entire network and identifying the best location, hence, requires a network-level analysis.

Location-allocation models are ideally suited to optimize the spatial configuration of a facility network of some type (e.g., retail centres, schools, etc.) These models rely on some method to search for a set of locations that is optimal in terms of a user-defined objective function and possibly one or more constraints. A well-known heuristic that can handle large solution spaces and has proven to be effective is the interchange algorithm. The interchange heuristic has been developed for a particular location-allocation problem, known as the p-median problem (Teitz and Bart 1968). However, Hillsman (1984) showed that the method is suitable for a much wider class of location-allocation problems. The heuristic assumes the number of service locations, p, as given and tries to find a selection of p locations among m candidate locations that maximizes the value of a given objective function within specified constraints (if any).

Therefore, the purpose of the present paper is to develop a method for generating land-use plans that combines location-allocation models and land-use allocation models. The proposed method uses the interchange heuristic for allocating service-type of land-uses and a swapping heuristic for dealing with area-type of land-uses. Allocating area-type of land-uses is based on conventional assumptions regarding the suitability function, but it uses a somewhat more refined allocation procedure. The purpose of the paper is to develop and empirically illustrate the new method. To that effect, the paper is structured as follows. In the next section, we will first briefly describe the two component heuristics involved, i.e. the interchange and swapping algorithm. Then, in the next section we describe the integration of the two heuristics in a single procedure. In the section that follows, we discuss the results of an application conducted to illustrate the method. Finally, we conclude the paper with discussing the major conclusions and suggestions for future research.

2. THE COMPONENT MODELS

2.1 The swapping heuristic

The allocation of area-type land-uses consists of two functional components, namely a method to determine the suitability of each location for each land-use and an algorithm to allocate land-uses to locations given the suitability scores. This approach corresponds to existing land-use allocation models. The way the components are specified, however, differs and, therefore, we explain the models in more detail in this section. First, we will explain the way the study area is represented.

Representation of the study area

Consider as given a study area represented as a grid of cells, a classification of land-uses and a task-size for each land-use in this classification. Cells are small enough to allow the assumption that each cell is covered by a single land-use. In the existing situation, each cell has a particular land-use. For (at least some of) the cells in the plan area, the existing land-use may be changed to some other land-use. The land-uses a cell is allowed to take is indicated by a vector of Boolean variables denoted as F_{ij} ($F_{ij} = 1$, if the j-th land-use is a possible future land-use of the i-th cell, and $F_{ij} = 0$, otherwise). If j' is the current land-use and the variable is zero for all $j \neq j'$ then we say that the current land-use is *fixed*, i.e. unable to be converted to any other land-use. A land-use will be considered fixed if the cell does not belong to the plan area, i.e. the area the planner considers for implementing new developments. A land-use may not be fixed and yet certain alternative land-uses may not be available for the cell. This may occur, for example, because land characteristics prohibit certain land-uses (e.g., the soil is not suitable for agriculture) or regulations prohibit a change to some other or to any other land-se (for example, locations with historical value that should be preserved).

The treatment of roads in the study area also deserves attention. A road is not considered a land-use. Rather the presence of a road is an attribute of a cell. In this way, we can represent a situation where the area a road covers is small compared to the total size of the cell. The land-use of the cell then represents the dominant land-use and the attribute indicates that the cell has a road. A situation where a road does cover the area completely or almost completely can be represented as well, namely by setting the land-use to Ignore, a special dummy land-use, and the attribute to presence of a road.

The suitability function

The suitability of a cell for a particular land-use depends on land characteristics of the cell, on distances, and on adjacencies to each type of land-use. For each land-use, the suitability of a cell is defined by

$$S_{ij} = \sum_{k} X_{ik}^{j} + \sum_{j'} D_{ij'}^{j} + \sum_{j'} A_{ij'}^{j} \qquad (1)$$

where S_{ij} is the suitability score of cell *i* for land-use *j*; X_{ik}^{j} represents the (weighted) score of land characteristic *k* of cell *i* regarding land-use *j*; $D_{ij'}^{j}$ is the score of the distance class representing the shortest distance from cell *i* to the nearest cell with land-use *j'*, for land-use *j* and $A_{ij'}^{j}$ is the score of the adjacency to land-use *j'* for land-use *j* in cell *i*. The land characteristics of a cell are not taken into consideration in this paper. The contribution of land-use *j'* at some distance from cell *i* may be both negative and positive and need not be linearly related to the (shortest) distance to land-use *j'*. Therefore, distance will be represented by means of classes for which specific suitability scores have to be specified. For example, if housing should be at some distance from a main road because of noise and pollution, but not too far away, the distance classes '0-500m' and 'more than 2500m' do not contribute to the suitability score while the in-between class '500-2500m' contributes significantly positive to the suitability score (see *Table 2* for an example). It should be noted that the distance scores are assumed to be weighted. In case *j'* represents a facility-type land-use (shopping centres, schools, etc.), the distance to the nearest *centroid* cell of the facility is used as well as the distance to the nearest cell with that land-use. The centroid-based distance is relevant from the point of view of accessibility to facilities, whereas by means of the land-use based distance one can take possible interactions between land-uses into account. In case *j'* is an area-type land-use, the distance to the nearest cell with land-use *j'* is used.

The adjacency score represents the effects of neighbouring cells. For example, for a housing cell it may be preferable to have similar cells as direct neighbours, while it might be less preferable to have a school as neighbour. Adjacency is defined at two levels. The first level represents the four lateral neighbouring cells, the second level represents the additional four corner cells. The user may differentiate between these levels when specifying the (weighted) effects of adjacency between any pair of land-uses. The adjacency score represents the weighted sum of effects across the neighbourhood cells.

Note that both distance scores and adjacency scores are determined given the existing situation in the (urban) surroundings and land-uses that have been allocated to cells in the plan area. As a consequence, the scores have to be updated each time a land-use has been assigned to a cell in the plan area.

The allocation algorithm

The algorithm assumes a predefined order of area-type land-uses to be allocated to the plan area. To start, the system determines the suitability score of each cell *i* available to the first land-use and allocates the first land-use to the best cell. Next, the system calculates the suitabilities for the second land-use in line, taking into consideration the allocation of the first land-use in the previous step. Again, the land-use will be assigned to the cell with the highest suitability score. This is repeated until the last land-use has been assigned. This procedure is repeated until the required number of cells has been assigned for each land-use. However, the suitabilities used in this initial round of allocations do not take adjacency scores into account (the last term on the right-hand-side of Equation 1). By not being sensitive for adjacencies, the model in this initial allocation stage is able to find 'intrinsically' good locations for land-uses.

Because the area-type of land-uses have been assigned on a cell-by-cell basis and adjacencies have not been taken into account, the resulting plan is not likely to be optimal. Therefore, the system initiates an optimization round. The total utility of the current plan is calculated as follows:

$$U = \sum_i \sum_j S_{ij} \times a_{ij} \tag{2}$$

where U is the utility of the current solution; a_{ij} is 1 if area-type land-use *j* has been assigned to cell *i*, 0 otherwise. The system starts swapping any pair of different area-type land-use cells across the plan area to improve the utility of the solution. After each swap, the system calculates the utility of the adapted situation using the same Equation (2). If the utility of the adapted situation is larger than the utility of the current situation (i.e. $U' > U$), the current situation is set to the adapted situation. Otherwise, the swap is reset. Anyway, the system continues swapping until no more swaps can be made to increase the utility of the current solution. The allocation of area land-use types is then completed.

2.2 Location-allocation models and the interchange heuristic

The basics

Schools, green parks and shopping centres are examples of service type of land-uses. These facilities are characterized by the fact that they satisfy some demand of a local population whereby users have to travel to the locations and are free to choose a location that provides the facility. Location-allocation models are suitable for such so-called user-attracting facility systems (Leonardi, 1981). In the most general formulation, these models intend to find the optimal configuration of a facility system (serving a local population) in terms of the number, location and size of outlets. Possibly, one or more constraints are formulated in terms of minimal performance requirements a solution must meet (e.g., a retail centre should be available within walking distance from each origin location).

Many location-allocation models have been described in the literature (for an overview, see Beaumont 1987). Arguably, two basic models are relevant and suffice for the purpose of the method developed here, namely the *p*-median model and the maximum-covering model. The objective of the *p*-median model is to find the locations of a given number of *p* facilities (e.g., shopping centres, schools or green spaces) that minimize the total distance users must travel to reach the nearest outlet from their origin location (usually, their residential location). The maximum-covering model, just as the *p*-median model, assumes the number (*p*) of facilities as given. In contrast to the *p*-median model, however, it assumes a certain pre-defined critical distance. An origin location is considered to be covered only if a facility is available within this critical distance. The maximum-covering model tries to find the *p* facility locations that maximize the number of users (or, more generally, the total demand) covered.

The interchange heuristic is an efficient and effective method to search solution spaces of this type. This algorithm developed by Teitz and Bart (1968) systematically evaluates marginal changes to an initial set of facility locations. An initial solution is supplied to the algorithm; this is the first *current* solution. The first candidate not in the current solution is substituted for each facility location in the current solution. The substitution yielding the largest improvement in the objective function value, if any, is selected for a substitution (interchange). When all of the candidates not in the current solution have been tested for substitution for all of the locations in the current solution, an iteration is complete. The algorithm terminates when no interchange was implemented in the last iteration.

Extensions

In the context of land-use planning, the number of facilities, *p*, is not given, but rather a facet of the solution that needs to be optimized. Furthermore, the facilities do not necessarily have the same size. We, therefore, use the interchange algorithm within a larger procedure that optimizes the size and number of facilities simultaneously with the location of facilities. The approach is based on a distinction between macro-strategy and location (or micro-)strategy proposed by Ghosh and McLafferty (1987). A macro-strategy defines the number of facilities and the size of each facility but does not specify locations. In the context of the land-use allocation problem considered here, the task size and, hence, the sum of sizes across facility locations is given. This means that there are as many possible macro-strategies as ways of partitioning a given task size. Clearly, the number of ways in which this can be done is virtually infinitely large if facility sizes can vary on a continuous scale.

We assume, however, that the macro-strategies a planner may consider are more qualitative in nature. Specifically, we assume that the range of potentially interesting solutions can generally be covered by as few as three more abstract macro-strategies for each facility system and each study area. These include a centralized, semi-centralized and a de-centralized strategy. The definitions of these strategies are based on a three-way classification of facility locations. In order of ascending size, this classification includes neighbourhood facilities, city-district level facilities and city-level facilities. The facilities of each order have a standard size, referred to as Small, Medium and Large. A decentralized strategy partitions the task size into Small facilities only, a semi-centralized strategy splits the total into Medium facilities (and forms Small facilities of the left over) and the centralized strategy creates as many as possible Large facilities (and forms first Medium and next Small facilities of the left over).

Note that within a macro-strategy, the number of facilities (p) is given implying that the interchange heuristic can be used to search for optimal locations. Having identified the optimal locations for each macro-strategy by means of the interchange heuristic, the macro-strategies can be evaluated and the one that maximizes some objective function can be identified as the overall best solution of the location problem. There are two issues that need more attention in this approach.

First, if a set of p facilities differ in size then there are two possibilities: they are either hierarchically structured or they offer the same service and just differ in capacity (i.e., the intensity of use they can support). Two facilities are considered of a different level if the larger facility offers all services the smaller facility offers and additional services as well. If facilities are hierarchically structured then a macro-strategy including k different facility sizes requires k times applying the interchange algorithm for generating a micro-strategy. Let $p_1 \dots p_k$ represent the numbers of facilities in the different size categories from largest to lowest size. Most naturally, we could follow a top-down approach where the interchange heuristic is run first to find the locations of the p_1 largest facilities, next to find the locations of the p_2 smaller facilities, taking into account the p_1 locations as existing competitors. This continues until in the last run the locations of p_k facilities are determined taking the locations of $p_1 + p_2 + \dots + p_{k-1}$ facilities into account.

On the other hand, if a set of p facilities differ in size, but are not hierarchically structured, then they all compete on the same level with each other. In that case, the interchange algorithm needs to be run only once to locate all p facilities simultaneously. If the maximum-covering model is used, the critical distance, i.e. the radius of the catchment area of a facility, could be set dependent on the size of the facility. A larger facility has a larger capacity and hence could attract people from a wider area. This can be represented by setting the critical distance to a larger value (simulating a larger catchment area). A similar measure is not possible for the p-median model and, therefore, we conclude that the p-median model is limited (or, stronger, not suitable) in a non-hierarchical, heterogeneous-size strategy case.

Second, having generated a micro-strategy for each macro-strategy in the way described above, the macro-strategies can be compared on relevant criteria. Where accessibility or coverage is a primary concern at the micro-level, a wider range of planning objectives is relevant at the macro-level. In particular, economic considerations play a role. Macro-strategies may differ in terms of the balance between costs of running a facility system and demand attracted to it. Centralized solutions benefit from economies of scale and, therefore, tend to perform better in terms of profitability of a facility system. Also, they may be preferred from the point of view of an efficient use of space.

3. THE INTEGRATED SYSTEM

Using the interchange algorithm on a grid of land-use data

The interchange algorithm assumes as input: a set of candidate locations, the locations of existing facilities (if any), the origin locations of demand (with associated demand weight) and a matrix of distances between demand and facility locations, and generates as output the allocation of new facilities, which may differ in size, to candidate locations. It is natural to interpret the point locations as centroids of the areas covered by facilities. Thus, in case of an existing facility we identify the most central cell as the location of the facility. In case of a new facility, on the other hand, we use the point location as a seed from which the area grows out in all directions until the area needed for the facility is realized. In this process, only those cells that are available for the conversion undergo the change. As a consequence, the resulting area for the new facility is not necessarily a contiguous area.

A next question is how we can identify candidate and origin locations based on land-use information. As *candidate locations* we consider all cells that are convertible to the land-use that corresponds to the facility considered. Compared to traditional applications where candidate locations are pre-selected, the resulting set of candidate locations will be very large for any study area of realistic size and spatial resolution (cell size). However, as it appears, the interchange algorithm is very efficient and still finds solutions in reasonable time for realistic dimensions of size and resolution of a study area (using a standard PC). The *origin locations* of demand are identified as all cells that have a land-use from which demand for the facility could originate. In case of most user-attracting facilities, the housing land-use is the main source of demand. If the land-use classification allows a differentiation in housing density, it is possible to use density as demand weight for each origin location. Land-uses other than housing may also be an origin for demand. For example, if one assumes that shopping trips may also originate from office locations, then cells including office activity may be identified as additional origin locations (of which the demand weight can be set to indicate the relative size of demand from such cells).

Once the origin and destination locations are known, the distance matrix can be calculated in conventional ways. If the actual or planned road infrastructure is known, distances can be calculated based on least-costs paths through the network. Otherwise, one should use metrics such as straight-line distances or Manhattan distances, etc.

The interaction between the interchange and swapping algorithm

Each facility type corresponds to a unique land-use. Therefore, if G denotes the number of facility types, then there are $H = G + 1$ processes involved to allocate land-uses to locations, i.e. G interchange-based processes to allocate the service-type land-uses and one swapping-based process to allocate the (remaining) area-type land-uses. In the following we will use the term agent to refer to a process. Thus, the system includes G service-agents that are specialized in a particular service land-use and one area-agent that takes care of the simultaneous allocation of area-type land-uses. We integrate the processes, by putting the agents in a sequence. The agent first in sequence generates a plan of his land-use(s) considering all cells convertible to his land-use(s) as candidate locations. The agent next in line then generates a plan of his land-use(s) considering all cells that are convertible to his land-use(s) and are not occupied by the first agent as candidate locations. This process continuous until the H-th agent has generated a plan of his land-use(s). Thus, an agent later in the process has, on the one hand, more information as he knows the land-use allocations of earlier agents and, on the other hand, less freedom of choice, as he may not use the cells claimed by earlier agents.

The plan resulting from this sequential procedure is not necessarily optimal from the point of view of each agent. An agent earlier in the process makes allocation decisions without knowing the actions of agents later in the process. Therefore, he may wish to reconsider his plan after the plans of agents later in the process have become known. To allow revisions, the above sequential procedure is repeated. In the second round, the agents successively reconsider their plans in the same sequence. Each agent earlier in the process is allowed to override claims of cells by agents lower in the process. This means that the set of candidate locations of each agent stays the same. Only the amount of information has changed: an agent earlier in the sequence can now adapt or in any other way respond to the land-use plans of the agents later in the sequence. After the second round, the state of the plan area will have been changed to the extent the agents have made revisions. The procedure is repeated until none of the agents makes revisions any more.

Revising a plan does not require a different heuristic. The same swapping and interchange algorithm is used for revision as for generating an initial plan. Recall that both algorithms – swapping and interchange – generate a solution in two stages. In the first stage an initial solution is determined and in the next stage this solution is optimized by applying swapping/substitution operations in an iterative procedure. The revision of a plan involves re-running the second optimization stage taking the current solution (for the land-use) as the initial solution. Thus, none of the agents starts from scratch in a revision round. Rather each agent tries to improve the current solution by a process of swapping land-uses between cells or by a process of relocating (centroids of) facilities, depending on the type of agent. It should be noted that, in case of service agents, there *is* a minor initialisation step involved: the cells currently occupied by the own land-use and that have a plan status are reset to the original land-use to simulate that the area of originally planned facilities is released.

Limited information and coping with uncertainty

All agents except the agent latest in the sequence have to deal with limited information especially in the first round of the procedure. For example, if the area agent responsible for housing and possibly other area-type land-uses is located later in the hierarchy than the retail agent, then the latter has to generate plans with limited information about which cells will become housing cells and, hence, about where the origin locations of demand will be. To deal with this type of uncertainty, each agent takes the *potential* land-use of a cell into account. For the service agents this means that each cell that is convertible to a housing cell is counted as a housing cell (with an average demand weight) even if the current land-use is other than housing. In other words, agents are optimistic and adopt best-case scenarios in case of uncertainty.

Generating alternative plans

The above iterative procedure results in a land-use plan for the study area. As discussed in Section 2.2, service agents may consider different macro-strategies for their land-use. The above iterative overall procedure is repeated under each combination of macro-strategies so that the system generates 3^G plan alternatives if each of the G service agents considers three optional macro-strategies for their land-use (e.g., a centralized, semi-centralized and decentralized strategy). In this way, the macro-strategies are evaluated under best micro-strategy choices of all the agents involved. Users are able to bring in whatever criteria they consider relevant for evaluation and making a choice.

The sequence of agents

The sequence of the agents is another parameter of the system that may have an influence on outcomes. It is plausible to assume that the land-use type that is most important for the structure of the plan area should be placed highest in the hierarchy. For example, the spatial pattern of shopping centres may have a relatively large influence on the structure of the plan area (e.g., central places of activities), which suggests that a Retail agent should be placed highest in the hierarchy.

4. ILLUSTRATION

The case considered

As an illustration, we consider the problem to generate a land-use plan for an area that has been allocated to accommodate the growth of a city. The expansion comprises an area of approximately 500 hectare and should accommodate approximately 6,000 dwellings. Table 1 represents the land-use classification used in this application and the task size for each land-use. Housing is subdivided into four housing types, namely detached houses, linked houses, row houses and apartments. The demand weights shown in the last column reflect the housing density, expressed as the number of dwellings per hectare, which varies across these housing types. The plan area can benefit from existing facilities in the city. Nevertheless, one or more shopping centres, schools and parks (for green recreation) need to be developed to serve the demands of the new population at a more local level. A 50 by 100 grid of 50-meter cells was used to represent the study area, which comprises the plan area, the immediate surrounding area and a part of the city. The task sizes shown in Table 1 are expressed in number of cells.

As Table 1 shows, the land-use classification used includes eight Area-type and three Service-type land-uses. We assume that industrial area and landscape have already been allocated meaning that the task size of industry and landscape is zero. The existing land-use of all other cells of the plan area is set to rest-green (i.e., undeveloped land); development of each land-use is considered possible in each of these cells. Thus, all agents can consider converting rest-green to their land-use in as far it has not been taken by agents earlier in the sequence. The swapping algorithm deals with the allocation of the four housing types. The interchange algorithm, on the other hand, considers the allocation of area for shopping centre(s), green park(s) and school(s). New facilities of these types have to compete with existing facilities in the city. These include three Large shopping centres (one on the south side and two on the west side of the city) and three Large schools (all located on the west side). There are no existing parks in the city.

The parameter settings of the suitability function used to calculate suitability scores reflect general (Dutch) planning standards. That is, housing prefers to be close to green, adjacent to housing of the same type, distant to industry, at some optimal distance from a road and close to retail, green and school facilities. In terms of accessibility, somewhat more weight was attached to apartment and row houses compared to the more expensive detached and linked houses (because the latter residents are often more mobile). In terms of environmental factors, somewhat more weight was assigned to the more expensive forms of housing. As an example, Table 2 shows the settings of the parameters of the distance function for detached housing. The columns represent the distance range (only the upper limit is shown) and the associated score for each distance class distinguished. Note that the facility land-uses (retail, schools and green spaces) appear twice in the table: above the dotted line as distance to land-use and below the dotted line as distance to centroid (differentiating between different size categories of the facility concerned, 1=largest, 3=smallest).

Table 1. Land-use classification and parameters of the case study.

Code	Land-use class	Land-use type	Task size (N cells)	Demand weight
1	Housing Detached	Area	215	2.8
2	Housing Linked	Area	268	5.6
3	Housing Row	Area	386	7.0
8	Housing Apartments	Area	130	9.3
4	Retail	Service	4	0
5	Green parks	Service	200	0
7	Schools	Service	4	0
6	Rest-green*	Area	0	0
9	Landscape	Area	0	0
10	Industry	Area	0	0
11	Ignore			

*Green land-use that remains if no specific development is implemented

Table 2. Example of a distance parameter table (Housing detached).

Land-use		Interval 1	Interval 2	Interval 3	Interval 4	Interval 5	Interval 6
Housing	D	< 60 (35)	< 110 (28)	< 160 (21)	< 210 (14)	≥ 210 (7)	
Housing	L	< 50 (5)	< 200 (15)	≥200 (25)			
Housing	R	< 100 (5)	< 500 (15)	≥500 (25)			
Housing	A	< 200 (5)	< 1000 (15)	≥1000 (25)			
Retail		< 500 (8)	< 1000 (6)	< 1500 (4)	< 2000 (2)	≥2000 (0)	
Green		< 100 (12)	< 200 (9)	< 400 (6)	< 800 (2)	≥800 (0)	
Schools		(0)					
Rest-green		< 1000 (8)	< 2000 (4)	≥2000 (0)			
Landscape		< 100, (12)	< 200 (9)	< 500 (6)	< 800 (3)	≥800 (0)	
Industry		< 500 (-10)	< 1000 (-5)	≥1000 (-1)			
Retail	1	< 800 (8)	< 1200 (6)	< 1700 (4)	< 2000 (2)	≥2000 (0)	
Retail*	2	< 600 (8)	< 900 (6)	< 1200 (4)	< 1500 (2)	≥1500 (0)	
Retail*	3	< 500 (8)	< 800 (6)	< 1000 (4)	< 1300 (2)	≥1300 (0)	
Green	1	< 500 (8)	< 800 (6)	< 1400 (4)	< 2000 (2)	≥2000 (0)	
Green*	2	< 250 (8)	< 500 (6)	< 800 (4)	< 1500 (2)	≥1500 (0)	
Green*	3	< 100 (8)	< 300 (6)	< 500 (4)	< 800 (2)	≥800 (0)	
Main road		< 500 (0)	< 1000 (16)	< 1500 (16)	< 2000 (16)	< 2500 (16)	≥2500 (0)
School	1	< 1000 (12)	< 1600 (6)	≥1600 (0)			
School*	2	< 1000 (12)	< 1600 (6)	≥1600 (0)			
School*	3	< 1000 (12)	< 1600 (6)	≥1600 (0)			

*Relevant only in case of hierarchical facility system

Table 3. Settings of the Service-type land-uses used in the case study.

Facility	Hierarchical	Type	Size (N cells)	Radius (m)
Retail	No	Large	4	900
		Medium	2	550
		Small	1	400
Green	Yes	Large	200	1000
		Medium	40	500
		Small	17	350
Schools	No	Large	4	900
		Medium	2	700
		Small	1	450

Table 3 shows settings that are used for the interchange algorithm. Only, green facilities are supposed to be hierarchically structured. That is, we assume that larger parks can accommodate more forms of recreation than smaller parks, whereas larger shopping centres/schools satisfy the same demands and differ only in terms of capacity from smaller shopping centres/schools. In all cases, the size of the catchment area is supposed to be dependent on facility size: larger facilities have larger catchment areas than smaller facilities. The radius of the catchment area for each facility type and each size class was set such that the plan area is just fully covered by the set of facilities that can be developed of that size class given the task size.

Results

The sequence of agents adopted in this case was as follows: 1) Retail; 2) Green; 3) Schools; and 4) Area agent (i.e., housing). Rather than using the stopping rule, we used a maximum of two cycles meaning that each agent has one opportunity to revise his plan. As it appears, all agents do revise their plans. The retail, green and school facilities tend to move somewhat towards the centres of high density housing. The housing agent then follows these moves in terms of moving clusters of high density somewhat closer to central places. As a result, after one revision round the solution is near to a state of equilibrium.

The computation time required for the interchange algorithm to generate a solution depends strongly on the model used. The *p*-median model requires much more computation time than the maximum covering model: 2.5 minutes versus 2 seconds. The larger computation time is a result of both longer time per iteration and a larger number of iterations. The computation time needed by the swapping algorithm is rather constant and of the order of magnitude of 3.5 minutes. The computation time for the overall algorithm, when the maximum-covering model is used by each service agent, is less than 10 minutes (on a standard PC).

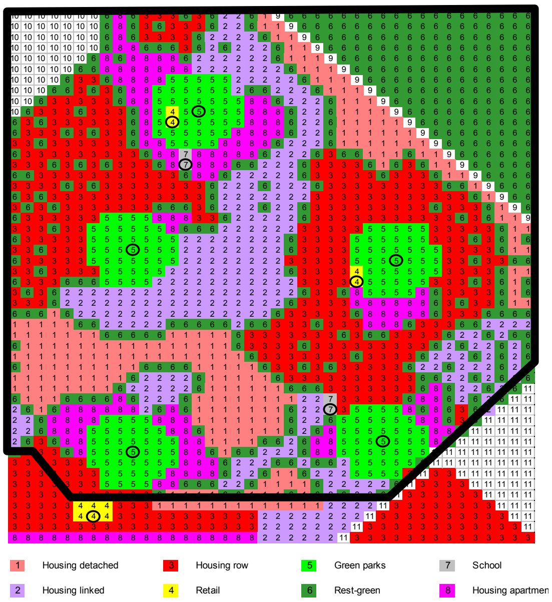

Figure 1. Example of a land-use plan generated by the system where service agents all use a semi-centralized strategy.

Because initial solutions of the interchange algorithm are random, we may expect differences in results across runs even if the settings are kept constant. As it appears, however, the solutions generated are robust for the initial solution, i.e. multiple runs give the same result, suggesting that the solutions found are indeed optimal. This statement should be nuanced for the maximum-covering model. In that case, the robustness depends on the setting of the radius of the catchment area. If this radius is too large or too small then there are many optimal solutions and the one generated, then, obviously will depend on the random solution. If the radius is set to an appropriate distance, the optimum is unique and the algorithm robust. The differences in solutions between the *p*-median and maximum-covering model tend to be fairly modest.

As an example, Figure 1 shows a land-use plan generated by the method where all service agents used a semi-centralized strategy and the maximizing-covering model. The figure shows only a part of the study area, to fit the width of a page. Not shown is the existing city on the west side of the plan area. The black line represents the borders of the plan area. The small circles indicate the positions of the centroid of each facility. Since all agents used a semi-centralized strategy, the facilities of each category are of a medium size. Given these sizes there are two shopping centres, two schools and four parks located in the plan area. There are some tendencies clearly visible. The higher density areas tend to be attracted somewhat stronger towards the centres formed by the facilities. This means that the semi-centralized solution gives rise to multiple centres in the arrangement of housing as well. Rest-green serves as green buffers between clusters of different housing types and between industry and housing.

5. CONCLUSIONS

In this paper we argued that service-type and area-type land-uses require different allocation mechanisms and combined suitable heuristics for each of these types in an integrated system. The case study conducted showed the application of the method and highlighted performance characteristics of the new algorithm. As it appears, the new algorithm generates a land-use plan in reasonable computation times. By explicitly representing macro-strategies of agents, the method also provides a way of generating a set of meaningful land-use plan alternatives. This is considered an important property of a land-use allocation model if it is to be used for planning support. Future research could focus on various ways of elaborating components of the method. The objective function could be elaborated to take other than demand-covering and accessibility considerations into account. Also, more sophisticated models of spatial choice behaviour of users of facilities could be incorporated. In particular, trip-chaining behaviour that leads to multi-purpose trips could be represented to take spatial agglomeration benefits into account in the allocation of facilities. Similarly, the suitability functions could be extended to take land-characteristics into account in addition to distance and adjacency considerations.

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