Urban growth control planning support system: Methodology, implementation and applications

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ABSTRACT: This paper investigated the methodology, implementation and application of the planning support system for urban growth control planning (UGC-PSS). Urban growth control has been a frequently mentioned conception in the field of worldwide urban planning. To address this issue, most literatures only focused on determining urban growth constrained level (e.g. construction forbidden area, construction limited area) or establishing urban growth boundaries. However, urban growth is generally constrained by many constrained factors (CFs) in form of several control indicators, such as land use type control, urban activity control, building height control, and underground development control, besides constrained level. Therefore, in the paper we novelly developed a PSS based on uniform analysis zone (UAZ), a data structure for vector dataset. In the PSS, various CFs and corresponding control indicators mentioned above were taken into account to analyze comprehensive and complex urban control system and support the scheme compilation of urban control planning. Negative urban form was also brought forward accordingly to explicitly show the combined constrain of urban growth by all control indicators. UGC-PSS we developed was capable of calculating UAZ-based planning control zoning scheme using the control indicators of all CFs, and outputting the scheme as many partitions automatically for the use of planning practices. UGC-PSS was empirically implemented using common commercial GIS platform and applied in urban growth planning of Beijing metropolitan area. It has been demonstrated to be capable to handle 60 constrained factors with different constrained indicators, as well as generate and output the massive planning scheme automatically, thereby increasing the planning efficiency effectively.

KEYWORDS: Urban growth control PSS; Uniform analysis zone; Negative urban form; Control factor; Beijing

I. INTRODUCTION

This paper is a case study of a planning support system for urban growth control, in which Beijing urban growth control planning was taken as an example to demonstrate the develop and application of planning support system (PSS). Generally, the encroachment of open space and natural resources caused by urban sprawl has drawn worldwide attention and led enormous challenges to human sustainable development. The possible negative impacts of sprawl includes increased land consumption, cost in infrastructure construction, commuting distances, traffic congestion, energy consumption, and air pollution (Burchell 1998; Anas and Rhee 2006). More and more scholars and governors start to concern urban growth control issue, and in the field of urban planning, many researches regarding urban growth control were conducted recently. However, little attention was paid to conduct urban growth control planning considering various control factors and their control indicators as well as the application of PSS in it.

Urban growth control is widely required in the planning practices of Europe, America, Japan and China. In Europe and America, aimed at alleviating negative effects of urban sprawl, the modes of urban growth control can be classified into four types: neotraditional development, urban containment, compact city, and eco-city. Recently, the urban containment policies, targeting at improving developing density and protecting open spaces, were extensively applied to control urban growth (Nelson and Duncan 1995). They usually included three forms, greenbelts, urban growth boundaries (UGBs), and urban service boundaries, all of which are aiming to contain the future urban form within the pre-defined boundaries in order to control urban sprawl and encourage “infill development”. They also advocated the adoption compact city and intensive forms (Echenigue 2005). In America, more than 100 metropolitan areas together with their sub-regions have adopted urban containment policies to control urban growth till 2004 (Nelson and Dawkins 2004), and the main purposes of the policies were to protect open space and improve the efficiency of urban land development (Nelson and Dawkins 1999; Pendall and Martin 2002).

In Japan, the “Planned Urban Area” policy is applied in land use planning to regulate urban growth. Urban development is generally restricted in order to protect the natural environment and control urban growth by the policy. However, during the high-speed growing periods, Japan did not implement the policy well, and urban growth was not effectively controlled, resulting in over-scattered urban form. Valuable lessons can be drawn from the experience gained in urban growth control of Japan. Meanwhile, in China, it is also required to establish construction-forbidden area and UGBs to control urban sprawl according to the latest “Urban and Rural Planning Act” taking effect on January 1, 2008. Besides, green belt policies were also implemented in some cities, such as Beijing and Shenzhen.

Generally speaking, according to the experience of Europe and America, as well as the practice of China, urban growth control should be viewed as a critical element in urban planning compilation.

Urban growth control in China were raised later than that in Europe and America, and green belts and UGBs, similar with adopted by Europe and America aiming to determine rigid control boundaries for urban growth or urban service functions and control the region beyond these boundaries strictly, are the main forms of urban growth control policies. In urban planning and management practices, these dual urban containment policies cannot effectively control urban growth, because the over-abstracted control means, "development permitted" and "development not permitted", can only be applied in the absolutely control area instead of those relatively control area. In the relative control area, not rigidly develop forbidden or allowed, it may be permitted of urban development according with some developing limitations, such as maximum (protecting the perspective of old buildings) or minimum (preventing flood invasion) building height, constrained land use types, constrained urban activities, and so on. Therefore, urban growth control can be divided into two classes, one is the absolutely control area forbidding all types of urban development and activities, and the other is the relatively control area allowing the developments meeting some designated requirements. To address this novel issue, we proposed the conception of "urban growth control planning" (UGCP), which was mainly applied to solve the complex problem of urban growth control (introduced specifically in the Second section of the paper). Differed from urban containment policies, UGCP needs not only establish boundaries restricting urban growth absolutely, but also put forward specific control requirements from the perspective of various control aspects in the regions where urban growth is relatively controlled.

To address UGCP issue, we might intend to refer to land-use suitability analysis, firstly proposed by McHarg (1969). It has been a mature analysis method in the field of land use planning to identify appropriate regions for various land use type (Diamond and Wright 1988; Carver 1991; Thill 1999; Sui 1993). To conduct land-use suitability analysis, Overlay function and multi-criteria evaluation (MCE) are generally combined to create zoning maps of suitability for different land use types. According to the above analysis of UGCP, land-use suitability analysis approach has its limit in simultaneously taking into account numerous control factors (CFs) together with their multiple control indicators involved in UGCP. For this reason, we developed an particular urban growth control planning support system (UGC-PSS), rather than employing land-use suitability analysis directly, to support the whole planning compilation process, including displaying control factors, calculating and exporting control scheme automatically.

The planning support system, as the generally acknowledged decision support system for urban planning, was considered to be the latest form of computer-aided planning system (Klosterman and Richard 1997; Brail and Klosterman 2001; Stillwell 2002; Geertman and Stillwell 2004). As the set of a series of computer software instruments, PSS develops simultaneously with computer software and hardware technology, and has been constructed mainly on the basis of such theory and technology as geographical analysis theory, programming models, geographic information technology, and visualization (Long, 2007). Besides, the fundamental characteristics of PSS are systemic, dynamic and interactive. Because the spatial distribution of control factors and the specific content of control indicators are all possibly temporally dynamic in UGCP, the planning scheme of urban control needs to be adjusted occasionally. Hence, UGC-PSS, a planner-oriented system, can adapt to the practical requirement through interacting with urban planners, carrying out re-calculation of the planning scheme, and outputting the scheme with high efficiency.

In this paper we will introduce the theoretical methodology, key techniques, dataset requirements, as well as the development and application of UGC-PSS. To begin with, we will discuss the nature of urban growth control planning in Section 2, and investigate corresponding planning support methods in Section 3. In Section 4, we will come to the implementation of UGC-PSS, and in Section 5 we will give the whole application process of UGC-PSS in the urban growth control planning of Beijing. Finally, in Section 6, we will complete the paper with conclusions and discussions of UGC-PSS.

II. URBAN GROWTH CONTROL PLANNING

In this paper, urban growth control planning is based on not only control factors distributions that curb urban growth, but their control indicators determined by existing files related with control factors, including laws, regulations, technical standards, research results, international treaties and agreements, as well as already approved plans. The approved plans may consist of geological hazard prevention, water resource protection, cultivated land protection, ecological space protection and so on, making UGCP be described as "to plan the plans". Generally, the foundation inputs of UGCP are control factors and corresponding control indicators, which is different from land-use suitability analysis based on natural elements like natural terrain, geological conditions, climatic conditions, soil types, etc.

Via reconsidering the process and the nature of urban growth, it can be treated as urban development and urban activities. Urban development can be divided into the categories of ground and underground. Accordingly, the essence of UGCP in the paper includes not only ground urban development, but also underground urban development and the corresponding urban activities. The view of urban growth control is practically three-dimensional and includes control aspects of development types, building height, city activities, as well as underground development. The tasks involved in UGCP are to demarcate control zones (*Z*) as to distinguish the rigid absolute control area and flexible relative control area, and then carry through more detailed control indicators from a three-dimensional perspective, utilizing four control indicators: construction height (*H*), underground development (*U*), urban activity (*A*) and land-use type (*T*) (see Long *et al.* 2006; He 2008).

The above five control indicators of control factors, reflecting the essential control for urban form in various aspects, can be defined as the term of negative form (NF) in this paper, since every control indicator has played a role for urban form by controlling development types, building height range, urban activities and underground development. Distinguished from other studies regarding urban form, NF does not recommend the some types of urban form to be developed, but rather provides the urban forms that are forbidden or restricted from the urban growth control perspective. In the process of urban growth, such forms should be controlled in every aspect mentioned above, otherwise ecological resources will be encroached, or risks related issues will be brought about. NF, as the final and three-dimensional production of urban growth control planning, can be applied to guide the determination of urban form in land-use planning, urban master planning or regulatory detailed planning.

UGCP aims to protect natural resources and prevent ecological and environmental and geological disasters during urban growth, through which urban form can be accordingly constrained three-dimensionally. To conduct UGCP, it firstly need identify the spatial distribution of the control factors, and subsequently demarcate urban space based on CFs to generate control cells, and lastly form the planning scheme through synthetic analysis basing on control indicators of every CF together with the spatial distribution of CFs, to manage urban growth control. The spatial distribution of CFs can be obtained through various departments of local government, and control indicators of CFs, as the important basis of UGCP compilation, mainly include the following aspects.

Control zone (Z): divided into absolute control class (J) and relative control class (X).

1) Absolute control (J): In this zone forbidden are all types of urban constructions, urban activities and underground developments. Absolute control zone, as the rigid control extent of urban growth (the other four indicators are null and of no need), is identical to the currently existing policy of the construction-forbidden area in China.

2) Relative control (X): In this zone exist strict constraints on urban constructions, urban activities or underground developments. Special requirements of other control indicators (such as H, U, A and T) need to be met to permit urban growth within the zone. Relative control, as the relative control extent of urban growth, is identical to the existing policy of the currently construction-limited area in China. However in China, the other four indictors are not definitely required simultaneously for construction-limited policy, which solely pays attention to the limited construction boundary for the planning practices.

a) Land use type control (T): The indicator refers to the forbidden urban land use types. This paper will only consider three types of land use, residential (R), commercial (C) and industrial (M). If there is no limitation on land use type, then the value of T is null

b) Construction height control (H): The indicator refers to the forbidden building height in meter. The control of height, from the perspective of the control factors, stands for the controlled height range, such as >27, <9, 9~27. If there is no limitation on the building height, then the value of H is null

c) Urban activities control (A): The indicator refers to four aspects, control of facilities destruction (a), control of pollutant emission (b), control of resource exploitation (c), and control of site occupation (d). Every aspect above mentioned has specific control content for urban activities, and details can be found in Beijing Municipal Planning Commission (2007). If there is no limitation on urban activity, then the value of A is null.

d) Underground development control (U): The indicator refers to whether the underground development is controlled, and if yes, U=1, otherwise U=0.

The relationship between control indicators is as shown in Fig. 1 (‘*J*’ stands for the absolute control zone, and ‘X’ the relative control zone).

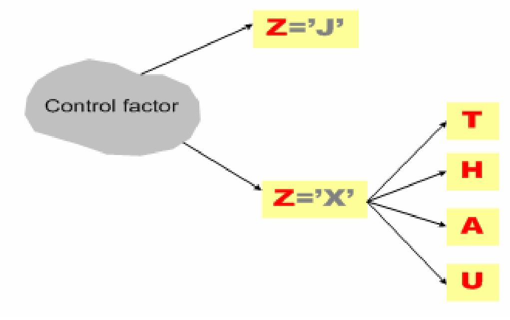


Figure 1. Relationship diagram of control indicators.

Regarding each control indicator of every control factor, we define the detail content of it as control element. For an instance, the control elements of the control indicator T are "R", "C" and "M". The relationship between control elements and control indicators is illustrated in (1), where $t_m, h_{p,} a_q, u_r$ respectively stand for control elements of control indicators T, H, A, U , m, p, q, r for total number of control elements in corresponding control indicator sets, K_T, K_H, K_A, K_U for control elements sets, i for control factor ID, I for total number of control factors, j for control indicator ID, l_{ij} for the value of the control indicator j for the control factor i, and L for the set of all control indicators for all control factors. From (1), we can see that for a control factor, its control indicator may include more than one control element. If $l_{ij} = \Phi$ (empty set), the control factor i is control free of the control indicator j. On the contrary if it includes all the control elements of the control indicator, namely $l_{ij} = K_j$, we call control factor i is absolutely controlled by control indicator j. Moreover, if all control indicators are absolutely controlled, $l_{iT} = K_r$ and $l_{iH} = K_H$ and $l_{iA} = K_A$ and $l_{iU} = K_U$, name the Z indicator of the control factor i is "J", standing for absolutely controlled.

$$
\begin{aligned}
&K_T = \{t_1, \ldots t_m\} \\
&K_H = \{h_1, \ldots h_p\} \\
&K_A = \{a_1, \ldots a_q\} \\
&K_U = \{u_1, \ldots u_r\} \\
&L = \{l_{ij} \mid i = 1, 2, \ldots, I,\ j \in \{T, H, A, U\}\} \\
&\text{where}\ \ l_{iT} \subseteq K_T, l_{iH} \subseteq K_H, l_{iA} \subseteq K_A, l_{iU} \subseteq K_U
\end{aligned} \tag{1}
$$

Control factor with all control indicators is corresponded with one NF. For example, Z denotes whether urban development is allowed. If *Z*='J', then urban development is forbidden absolutely, and NF is a purely natural landscape. *H* and *T* play a control role for the ground urban form. *A* controls urban activities within the urban form, and is concerned mainly with social space. *U* controls the underground development of the urban form. The relationship between these five indicators and NF can be expressed by (2). We divided the whole study area into two parts, negative form and urban form, from the view of T, H, A, U . Negative form, as a four dimensional set or vector, will be focused in this paper, through which we can draw primary conclusion for the selection of urban form.

$$
\begin{aligned}
&F = \{UF \cup NF\} \\
&UF = \left\{x \mid x \in F, x \notin NF\right\} \\
&NF = \left\{(T, H, A, U)\right\}
\end{aligned} \tag{2}
$$

F : Study area (Region)

UF : Urban form

NF : Negative form

In (2), *H* controls the construction height of NF. *T* controls the land use type of NF. *U* controls the underground development of NF. *A* controls the types of urban activities within NF. Because there is a whole set of control indicators in every control factor, every control factor corresponds to a kind of NF. The corresponding NF of selected control factors of Beijing metropolitan area is shown in Fig. 2.

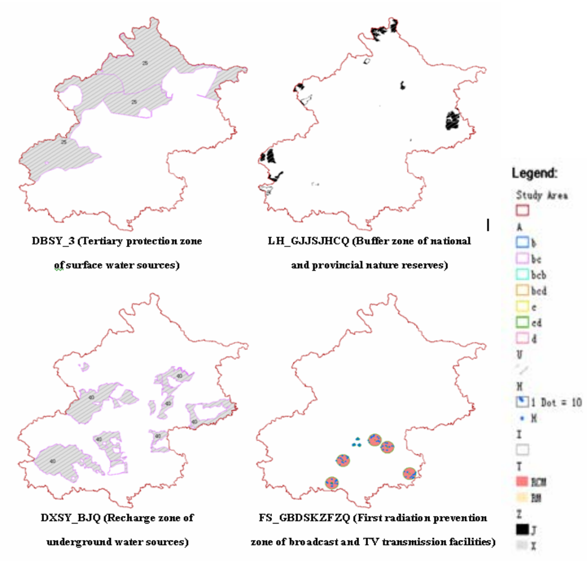


Figure 2. Negative urban forms for four control factors.

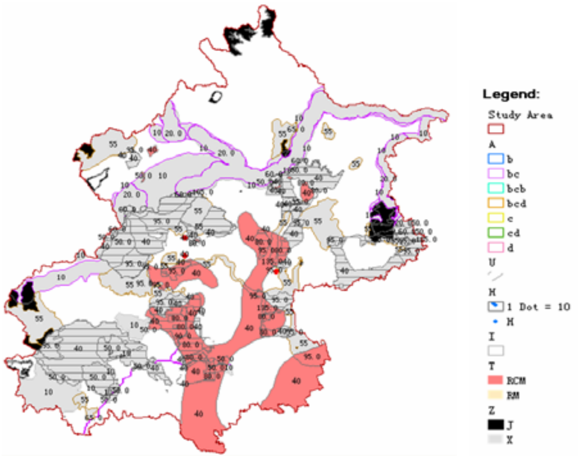


Figure 3. Negative urban form for control cells.

To address the overlapping issue of multi control factors, the term of control cell *y* is novelly bought forward, standing for the combined control factors in the same geographical space. Since each control factor is corresponded with one NF, every control cell also stands for one NF which is the integrations of NFs of control factors (see Fig. 3), and is the basic analysis unit of UGCP. The calculation method of the control cell using control factors will be investigated in detail in the next section.

In view of the complexity of factor composition and spatial distribution of control cell as the basic analysis unit of UGCP, a planning support system based on GIS was then developed to assist the complication of UGCP in which the NF of every control cell was then calculated. In the next section we will introduce the method of PSS to support the planning, including the generation of the control cell, calculation and output of the UGCP scheme.

III. METHODOLOGY OF PLANNING SUPPORT

A. *Generating control cells*

From the perspective of UGCP, UGC-PSS is required to be capable of not only calculating planning regime using numerous control factors and their control indicators, but exporting the calculated planning regime automatically. To meet the system requirement, we chose the uniform analysis zone (UAZ), a vector data format of irregular polygon, for UGC-PSS as the basic data model to express the control cell (in the following context, the term UAZ can be regarded as the control cell), namely NF. UAZ was first brought forward by Klosterman (1999) and introduced into his planning support system What if?. In What if?, UAZ is the fundamental analysis unit of modules such as Land Suitability Evaluation and Land-Use-Demands Allocation. In the California urban future model (CUF) for simulating urban development by Landis (1994, 1995), the fundamental modeling unit is a developing land unit (DLU) which is similar with UAZ in that they both are based on irregular polygon. Distinguished from What if? and CUF, UGC-PSS emphasizes the consideration of natural resource protection and risk prevention in urban growth control rather than only urban growth itself.

In view of the large number of control factors as well as complex control indicators of every control factor, we will take the virtual region, with three control factors, as an example to illustrate how control cells and corresponding planning indicators can be achieved using UAZ data model (see Fig. 4, grey square area is the virtual region). Using GIS spatial analysis toolbox UNION and UAZ data model, UGC-PSS can easily generate a UAZ layer, denoting the spatial distribution of control cells employing control factors datasets, the basic system inputs. UAZ's attributions, namely planning indicators standing for the UGCP scheme, can be calculated using control indicators of those control factors belonging to the UAZ. Generated control cells are then applied to calculate and output the planning scheme, which will be discussed in the near following sections.

We will come to discuss the benefits and drawbacks of introducing UAZ data model into UGC-PSS since it plays an important role in the system. The traditional suitability analysis is generally carried out based on the map algebraic operation of raster datasets. Regarding the benefits of using UAZ data model, firstly, compared with the data model of regular rectangle raster, it is scale free and is capable of recording plenty attributions to support model calculation, which is not easy to be achieved using the raster data model. Secondly, after UAZ dataset is created, UGC-PSS calculates the attributes of UAZs to achieve the goal of scheme calculation, thus providing it possible for researchers to focus on mathematical algorithms rather than the system interfaces, such as GIS spatial analysis. Thirdly, if control indicators of control factors are changed, the scheme can be recalculated and exported conveniently via revising the control indicators table without modifying the code of the system. However, the disadvantage of the UAZ data model lies in the fact that its time consuming is generally huger than the raster data model using map algebraic operators. When the total number of UAZ reaches to 400,000, the calculation time is about ten hours on a PC with CPU frequency of 6.0 G HZ (double CPUs). Therefore, the arithmetic in UGC-PSS needs be further optimized in near future.

B. Calculating planning scheme

In this paper, the term of "planning scheme" is defined as the control cells together with their planning indicators. Equation (3) shows how to calculate the planning scheme using control factors and their control indicators. In (3), UAZ stands for generated control cell dataset using UNION processing tool, x for its ID, uaz^x for a control cell, $uaz_j^{\ x}$ for planning indicator j of the control cell uaz^x, s_x for control factors set contained in uaz^x, $\bigcap_{i \in s_x}^{spt}$ for overlaps space of control factors s_x (intersection set in spatial), and f^j for the function to calculate planning indicator j.

$$
\begin{aligned}
&UAZ = NF = \{(T, H, A, U)\} \\
&UAZ = \{uaz^x \mid x = 1, 2, 3, ..., X\} \\
&uaz^x = (uaz_T^{\ x}, uaz_H^{\ x}, uaz_A^{\ x}, uaz_U^{\ x}) = l^{s_x} = \bigcap_{i \in s_x}^{spt} l_i \\
&uaz_j^{\ x} = \underset{i \in s_x, j \in \{T,H,A,U\}}{f^j} (l_{ij})
\end{aligned}
\qquad (3)
$$

As shown in (3), planning indicators are respectively corresponded with control indicators in the planning scheme, sharing the same names. The planning indicators can be calculated by the control indicators of control factors contained in the control cell. However, the calculation method (f^j) of each planning indicator may vary from each other.

C. Outputting planning scheme

The planning scheme needs show the spatial distribution of the control cells as well as the planning indicators of each control cell, and also requires necessary map elements. Since the complexity of control factors and the massive amounts of control cells generated make it difficult to express the planning scheme in a single page, we partition UAZ2 dataset of the whole study area into multiple partitions, according to the requirement of result display. For instance, partitions can be generated by dividing the study area into several rows and columns, or according to the standard map scale, such as 1:25,000, 1:10,000, and 1:2,000, etc.

The partitioning procedure is shown in "4. Output planning scheme" in Fig. 4, and its basic method is as follows. Firstly, a polygon dataset is created on the basis of

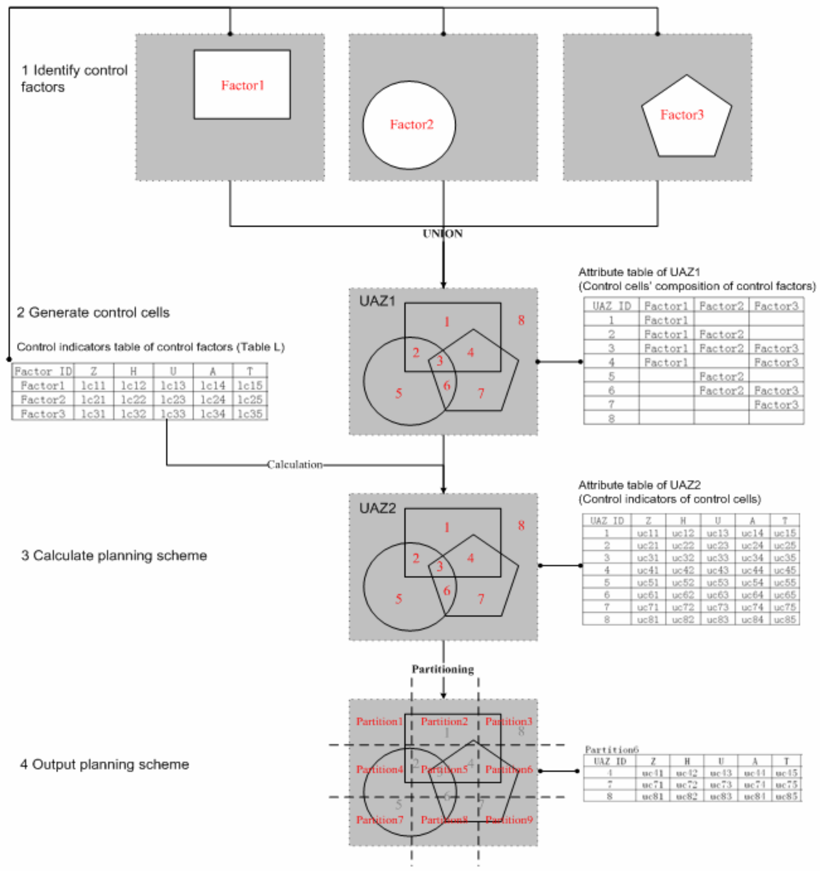


Figure 4. Flow diagram of planning scheme automatically calculation and output.

the choice of partitioning means to record the distribution of various partitions with every polygon standing for the spatial extent of a partition. Secondly, according to the spatial extent of a partition, the extent of map control as the output extent of spatial datasets within the partition is set, and control cells in UAZ2 dataset within the partition are selected using spatial analysis functions. The attribute table of those selected control cells within the partition is outputted as planning indicators table. Thirdly, the auxiliary map elements are added to the map, such as title, legend, compass, scale, and the partitioning index map. Finally, the print configurations are set, and the partitions can be printed on paper, or exported as JPEG digital files.

IV. SYSTEM IMPLEMENTATION

UGC-PSS we developed mainly consists of six modules, system configuration, spatial dataset display, comprehensive query, control cells generation, planning scheme automatically calculation, and planning scheme automatically output, and the last three modules are the core modules of UGC-PSS. During operating UGC-PSS, users log in the system through the common user interface, set system configurations, load the corresponding required basic datasets including control factors, and set the display parameters. After displaying the basic analysis environment, on one hand, users can conduct dataset queries from aspects of attributes and spatial properties, and analyze the construction conditions objectively within a given area. On the other hand, the module of control cells generation can be employed to create control cells using control factors, and then the corresponding planning control indicators can be calculated accordingly. Moreover, the scheme of UGCP can be exported automatically using the module of planning scheme automatically output. The fundamental structure and application flow of UGC-PSS are as shown in Fig. 5.

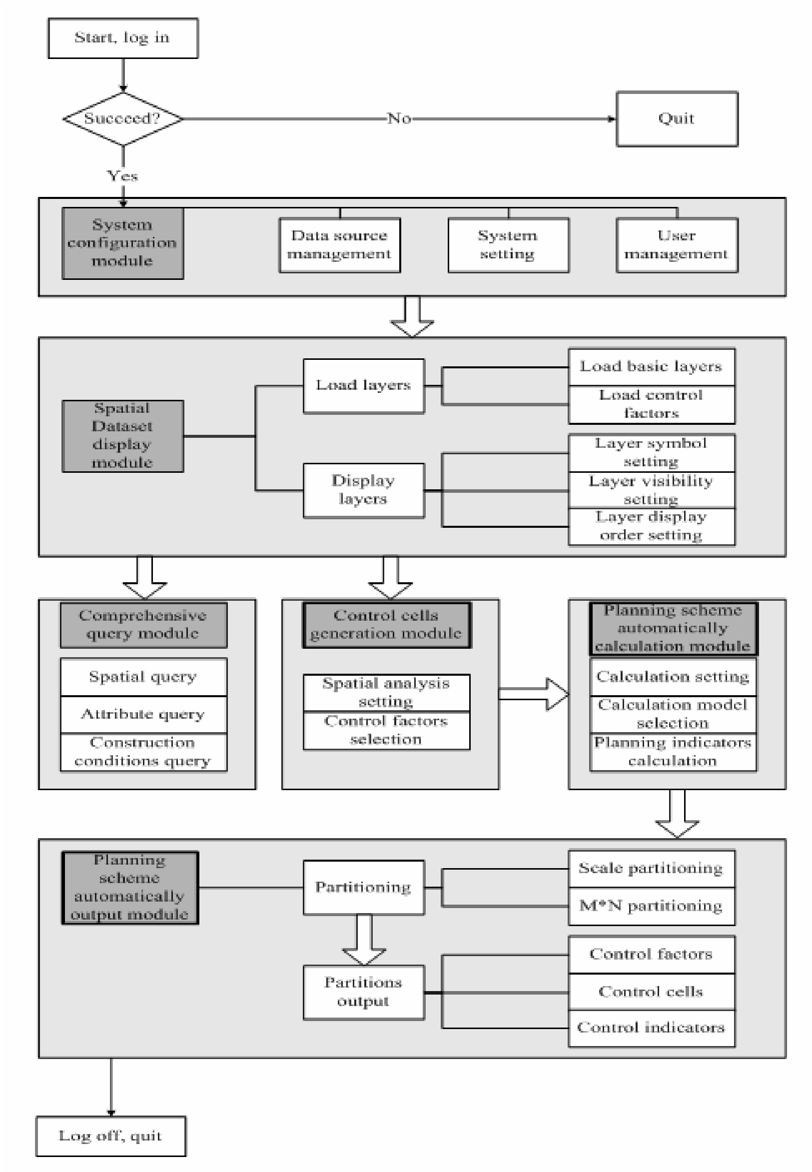


Figure 5. Framework and flow diagram of UGC-PSS.

Based on above diagram, UGC-PSS was developed using ESRI ArcGIS Engine 9.0 by Visual Basic 6.0, while planning scheme automatically calculation module was developed by Visual C++ for the purpose of promoting computational efficiency. The database platform used is ESRI Personal Geodatabase based on Microsoft Access. As shown in Figure 6, the main interface of the system is composed of seven parts, including title bar, menu bar, toolbar, map window, layer control window, thumbnails window and query results output panel. It is possible to perform data browsing, query and other related functions through the main graphic user interface, while further system functions can be achieved through entering the menu bar.

Specially, through planning scheme automatically output module, as shown in Figure 7, UGC-PSS can load the planning scheme calculated by planning scheme automatically calculation module, add map elements, set the corresponding partitions form, and generate the massive planning scheme automatically. Since ArcGIS Engine does not sufficiently support map partitions, ActiveReport 2.0, a third-party component, was used mainly to create multi-partitions.

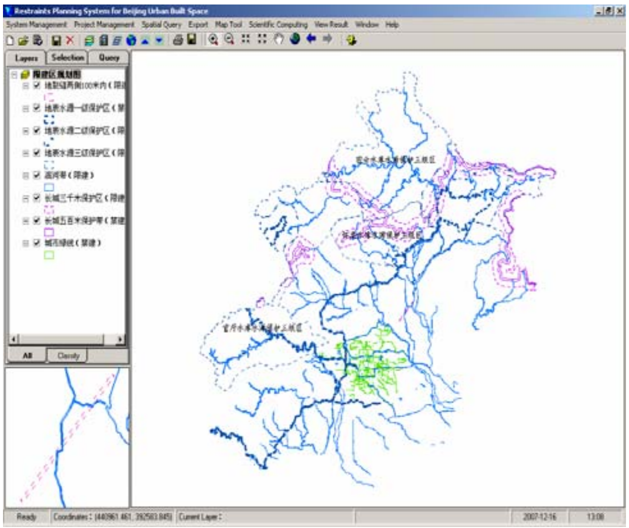


Figure 6. The main graphic user interface of UGC-PSS

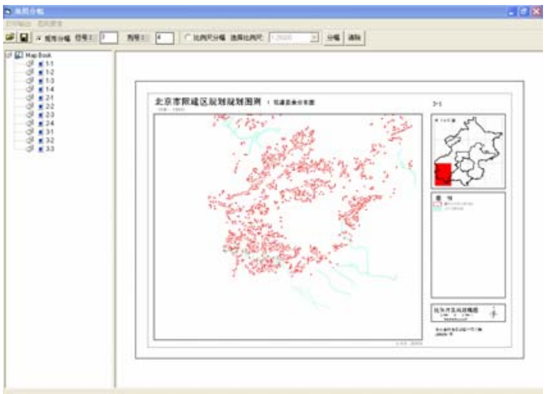


Figure 7. Graphic user interface of planning scheme automatically output module

B. *Dataset*

The basic datasets used in UGC-PSS mainly include fundamental terrain datasets, administrative division boundaries, control factors, and so on. The fundamental terrain datasets are topographic maps of different scales, aerial maps with one-meter resolution, digital elevation models (DEM), existing roads, existing wetlands, current land use maps, and urban master planning scheme. Administrative division boundaries are district, town and ward level boundaries. The former two types of datasets, which are not involved in the calculations of UGCP scheme, are mainly employed to spatially express the planning scheme as the base map and assist spatial queries.

V. SYSTEM APPLICATIONS

A. *Study area*

During the process of rapid development in Beijing, the tendency of disorderly urban expansion has not been effectively controlled even until now. Within Beijing metropolitan area, the urban growth is restricted by many control factors. Beijing urban growth control planning was developed to solve the adverse issue originated by urban growth in mega metropolitan, and UGC-PSS played an essential role in planning support. The spatial planning extent of the planning is Beijing metropolitan area (Figure 8) with an area of 16,410 km^2, which lies in northern China, to the east of Shanxi altiplano and south of Inner Mongolia altiplano. The southeastern part of study area is plain, with a distance to Bohai sea of 150 km. It is covered by mountainous area with an area of 10072 km2, 61% of the whole area.

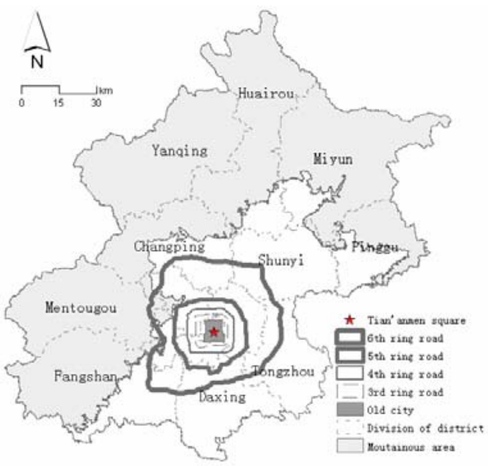


Figure 8. Fig.8 Study area map of Beijing metropolitan area.

Control factors are of the most important datasets of UGC-PSS. Within the study area, there are 60 control factors controlling urban growth, including water conservation, biodiversity conservation, agricultural land protection, flood control, geological disasters prevention, steep slope areas, pollution source protection, and so on. Within the spatial distribution of each control factor, control guidance remains the same, or it needs to be subdivided into new control factors.

In Beijing, the control elements of each control indicator is respectively $K_T = \{"R","C","M"\}$, $K_H = [0,1000)$, $K_A = \{"a","b","c","d"\}$ (the meaning of each elements is introduced in Section 2), and $K_U = \{1\}$. The names and control indicators of these items are listed in Table 1 (corresponding with the "control indicators table of control factors" in Fig. 4), and the spatial distribution of every control factor is available in Beijing Municipal Planning Commission (2007).

TABLE I. INVENTORY OF CONTROL FACTORS AND CORRESPONDING CONTROL INDICATORS

ID	Name	Description	Z	H	U	A	T
L020002	DBSY_2	Secondary protection zone of surface water sources	X			b	R C M
L020003	DBSY_3	Tertiary protection zone of surface water sources	X			b c	
L040002	DXSCC_YZCCQ	Over exploited area of underground water	X			c	R M
L030002	DXSY_BJQ	Recharge zone of underground water sources	X		1	b c	
L030003	DXSY_FHQ	Protected zone of underground water sources	X		1	b c	
L120004	DZ_JC	Area with poor engineering geology	X	>45			R C M
L140008	DZZH_DLF500	100m to 500m buffer zone of ground fissures	X				RM
L160001	FS_GBDSFHQ	Secondary radiation prevention zone of broadcast and TV transmission facilities	X			c d	
L160002	FS_GBDSKZFZQ	First radiation prevention zone of broadcast and TV transmission facilities	X	>120		c d	R C M
L150006	HJ_FBCLC	Prevention zone of nightsoil treatment plants	X				R C M
L150003	HJ_LJDFC	Prevention zone of waste compost plants	X				R C M
L150005	HJ_LJFSC	Prevention zone of waste incineration plants	X				R C M
L050001	HLTX_GFXQ	High-risk area of flooding	X			d	
L070004	LD_EGLD	Existing forests in the second greenbelt	X				R C
L070002	LD_YGFW	The first greenbelt	X	>18			
L060009	LH_FJMS2	Secondary protection area of scenic spots	X	>9		b c d	
L060010	LH_FJMS3	Tertiary protection area of scenic spots	X	>18		b c d	R M
L060012	LH_GHFJMS	Planned scenic spots	X	>27		b c d	
L060005	LH_GJJSJSYQ	Experimental zone of national and provincial nature reserves	X			b c	
L060003	LH_SLGY	Forest parks	X	>21		b c	
L060006	LH_XJ	Nature reserves of county level	X			b c	R M
L060011	LH_XZQTFJMS	Other existing scenic spots	X	>21		b c d	R C M
L060002	LH_YBSTGYL	General ecological forests	X			c d	RM
L080003	ND_YBGD	General cultivated lands	X			c	RC
L080002	ND_YBND	General farmlands	X	>9	1	b c d	
L010003	SD_BHD	River buffer zone	X			a b c d	R C M
L010004	SD_KBD	Reservoir buffer zone	X			a b c d	

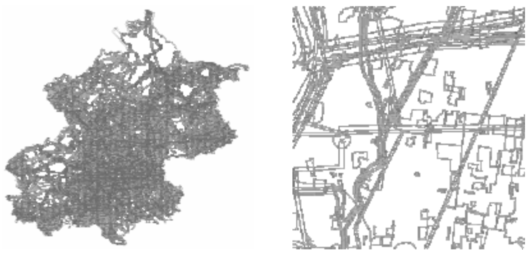
ID	Name	Description	Z	H	U	A	T
L090007	STLS_SQSTBHQ	Piedmont Ecological protection zone	X			b c	R
L170007	SZTD_NSBD	Protection zone of South-to-North water diversion infrastructure	X			d	
L170002	SZTD_TRQSY2	Secondary protection zone of oil/gas pipelines	X			d	
L100002	WW_CC3000	Three kilometers buffer zone of Great Wall	X	>9			
L100003	WW_DX	Protection area of underground cultural relics	X	>15			
L100004	WW_LSWH	Protected area of historical culture	X	>15			
L180008	ZS_CSDL2	Secondary noise prevention zone of city roads	X				R C
L180006	ZS_QG2	Secondary noise prevention zone of light rails	X				R C
L180016	ZS_SDJC3	Tertiary noise prevention zone of Capital International Airport	X				R M
L020001	DBSY_1	First protection zone of surface water sources	J				
L160003	FS_110	Radiation prevention zone of 110KV power stations	J				
L160004	FS_220	Radiation prevention zone of 220KV power stations	J				
L160005	FS_550	Radiation prevention zone of 550KV power stations	J				
L050006	HLTX_FHKM	Flood diversion gates	J				
L050004	HLTX_ZXC	Flood detention area in central city	J				
L070008	LD_XXLDLSKJ	Green wedges	J				
L070001	LD_YGLD	Planned green lands within the first greenbelt	J				
L060008	LH_FJMS1	First protection area of scenic spots	J				
L060007	LH_FJMST	Special grade protection area of scenic spots	J				
L060004	LH_GJJSJHCQ	Buffer zone of national and provincial nature reserves	J				
L060013	LH_GJJSJHXQ	Core zone of national and provincial nature reserves	J				
L070006	LH_LD	Green lands in central city	J				
L060001	LH_ZDSTGYL	Key ecological forests	J				
L080001	ND_JBNT	Basic farmlands	J				
L010001	SD_HL	River type wetlands	J				
L010002	SD_KT	Pond and reservoir type wetlands	J				
L090006	STLS_25D	Steep area with the slope greater than 25 degree	J				
L170004	SZTD_110	Prevention zone of 110KV transmission lines	J				

ID	Name	Description	Z	H	U	A	T
L170005	SZTD_220	Radiation prevention zone of 220KV power transmission line	J				
L170006	SZTD_550	Radiation prevention zone of 500KV power transmission lines	J				
L170001	SZTD_TRQSY1	First protection zone of oil/gas pipelines	J				
L100001	WW_CC500	500 meters buffer zone of Great Wall	J				
L100006	WW_WWDW	Protected historical units	J				

a.The meanings of the indicators in the inventory refer to Section 2 “Urban growth control planning”

C. *Applications in Beijing*

In Beijing urban growth control planning, UGC-PSS played a role of planning compilation support from the beginning. Most importantly, the system can perform the functions of calculating and output the planning scheme, a tedious work in planning practices. Control cells are created based on control factors (Fig. 9), and 60 items of control factors generate nearly 356689 control cells. Basing on the processed control cells dataset, the planning scheme of UGCP was then calculated with 9.5 hours consumed using methodologies in Section 3.



(a) (b)

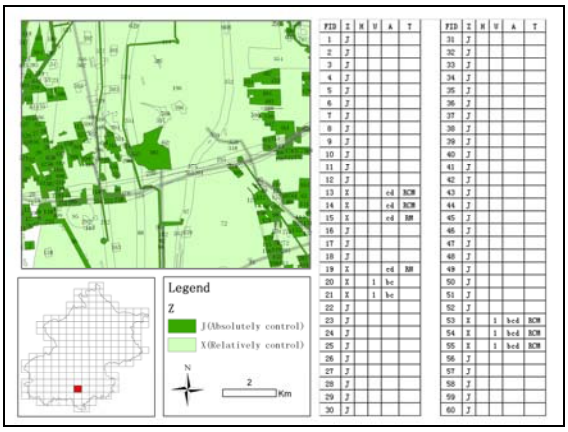
Figure 9. Spatial distribution of control cells in the Beijing metropolitan area : (a) the whole study area; (b) partial zoomed-in area.

The calculation function for each planning indicator is shown in (4). We simplified the calculation process in Beijing case, and all the planning indicators shared the same calculating function, union of sets. That is to say, the planning indicator value equals to the union of corresponding control indicators of control factors contained in the control cell.

$$f^T = f^H = f^A = f^U = \bigcup \tag{4}$$

The calculated planning scheme could be expressed and exported as digital pictures or paper drawings as for decision makers’, planners’ or public reference. The spatial distribution and attribute table of control cells obtained, as well as the base map dataset, were utilized to express the planning scheme. For the complexity of urban growth conditions in the study area, in Beijing planning we partitioned the whole study area into 213 partitions using the spatial scale of 1:25,000. The planning maps, exported by UGC-PSS, are shown in Fig. 10 and Fig. 11. In Fig. 10, control factors in the partition were rendered and displayed together with their legends. The control factors map can be used as a medium to understand the basic situation of urban growth control. In Fig. 11, the spatial distribution of control cells and the corresponding planning indicators are shown. The figure can also be regarded as NF information within

Figure 10. Spatial distribution of control factors of a partition



FID	Z	H	U	A	T	FID	Z	H	U	A	T
1	J					31	J				
2	J					32	J				
3	J					33	J				
4	J					34	J				
5	J					35	J				
6	J					36	J				
7	J					37	J				
8	J					38	J				
9	J					39	J				
10	J					40	J				
11	J					41	J				
12	J					42	J				
13	X			cd	BCM	43	J				
14	X			cd	BCM	44	J				
15	X			cd	BM	45	J				
16	J					46	J				
17	J					47	J				
18	J					48	J				
19	X			cd	BM	49	J				
20	X		1	bc		50	J				
21	X		1	bc		51	J				
22	J					52	J				
23	J					53	X		1	bcd	BCM
24	J					54	X		1	bcd	BCM
25	J					55	X		1	bcd	BCM
26	J					56	J				
27	J					57	J				
28	J					58	J				
29	J					59	J				
30	J					60	J				

Figure 11. Control cells distribution map and the first page of planning indicators table (Occasionally, planning indicator *H* is controlled free in this page)

the partition. It should be pointed out that if there are excess control cells which make it impossible to list the planning indicators within one page, UGC-PSS can export the planning indicators information automatically in multi-page format.

UGC-PSS, as the carrier of Beijing urban growth control planning, was applied to a number of urban and rural planning practices in Beijing, such as the coordinated planning of the eastern part of Beijing, the coordinated planning of the western part of Beijing, zoning for the central city, the plans of 9 new cities and 12 towns, and Badaling-Ming Tombs scenic area plan. The PSS was also applied in many cases of urban growth control condition comprehensive queries by urban planners. Moreover, UGC-PSS, as the medium of urban growth control, will be potentially applied in other planning practices related with urban growth. In practice, the application of UGC-PSS improved the compilation efficiency of UGCP considerably, and reduced the time consumed to establish and express the planning scheme by over 90%. Meanwhile, as a platform for planning scheme queries, it promoted the implementation of Beijing UGCP.

VI. CONCLUSIONS AND DISCUSSIONS

UGC-PSS proposed in this study offers a platform for urban growth control analysis, in that it can consider amounts of control factors in a framework synthetically and carry out the calculation and output of the planning scheme automatically. In UGC-PSS of Beijing metropolitan area, 60 control factors together with their control indicators were taken into account to reflect the urban growth condition in the study area. The PSS enabled solving complex urban growth control issue in mega metropolitan area, and has significant benefits on promoting planning efficiency and accuracy.

However, control factors and control indicators of them in current UGC-PSS are not adequate enough to express urban growth control system. On one hand regarding control factors, due to limited datasets availability, some control factors were not included in the empirical PSS of the paper, such as military protection zone, protected cultural & historical sites in the central city, environmental capacity and resource carrying capacity. Therefore, further improvement needs to be achieved of UGC-PSS in the near future reflect more objective and comprehensive urban growth control in Beijing. On the other hand regarding control indicators of control factors, we will refine the indicators of underground development control, which will be expressed by detailed control contents or types instead of by 1 or 0 currently. Moreover, more control indicators, such as construction floor area ratio (FAR) control and construction density control, will be considered in further study to enrich the framework of NF, which can be used for the urban growth analysis and simulation as the constrained condition of future urban form. Meanwhile, we also intend to upgrade UGC-PSS into web based PSS to facilitate more end-users as the platform for public participation in urban growth control planning.

In UGC-PSS, the method of planning scheme calculation using UAZ with several planning indicators are not only suitable for the research on urban growth control, but also can be applied to urban growth research conditioned that more factors regarding urban growth promoting are further considered in it, such as institutional factors and accessibility factors (a preliminary attempt has been conducted in Long et al. 2008ab). The prototype of UGC-PSS can also possibly be applied to other geographic analysis and geocomputing fields, which are effected by various spatial factors with different influencing indicators. Furthermore, we can introduce cellular automata (CA) to UGC-PSS, regarding every UAZ as a vector CA cell, to analyze and simulate more realistic urban growth control process.

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