SIMULATION AND ASSESSMENT MODEL OF URBAN DEVELOPMENT

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Abstract. The goal of the research presented was to create the tool that could help to define, predict and assess ex-antem sustainability of plans for development of an urban territory. The tool is intended for simulation of urban development dynamics on local scale (urban municipality). The dynamics of the model is above all influenced by positive and negative externalities from uses in immediate neighbourhood, spatial accessibility of the site, spatial accessibility of the infrastructure, spatial and functional constraints of spatial development declared as by-law regulatives, and transformation costs connected to change from one function to another.

A cellular automaton was selected as the best way to represent the spatial influences of various land-uses. Space is represented by one-dimensional or multi-dimensional grid of cells. Each cell has a certain number of neighbourhoods depending on the defined size of neighbourhood. In the model, each cell represents one type of land-use. The change from one land-use type to another is determined by the transition rule. Multiple factors (neighbourhood effects, relative accessibility and cost of land-use type change) enter the transition rule leading to the best possible use from the point of view of a single cell. The case of a suburban town of Říčany next to Prague is used for the model testing and calibrating.P okud je článek v českém nebo slovenském jazyce, je nutné uvést stručnou anglickou anotaci v rozsahu úvodního abstraktu. První věta anglického abstraktu bude do angličtiny přeložený název příspěvku.

Keywords: urban growth modelling, urban simulation, cellular automata

1 Introduction

The goal of the research was to create a model that would enable to predict the impact of the planning instruments (planning documents, prescriptions and regulations) on the future quality of the environment. The model will serve as a method to assess the sustainability of the territorial development and the contribution of planning instruments to “good” management of the territory. It was developed for simulation of urban development dynamics on local scale (urban municipality). To calibrate and demonstrate the model performance, the case of a suburban city Říčany next to Prague was used; other case studies are planned to be made.

Several requirements result from this goal, the tool should:

- Present alternative scenarios of future development in long term horizon;
- Enable a user to evaluate the effectiveness of the investment into public infrastructure and the impact of the land-use control;
- Be adaptable to locally available data; it should be accessible to experts as well as to the public without requiring excessive technical equipment on the part of the user.

The development of the model is currently in the phase of testing but even now it has certain values in understanding the relation and mechanisms that act in urban development. This article describes the basic assumptions and principles the model is built on.

2 Assumptions of the model

2.1 Background, concepts and functional structure of model

The model is based on the following assumptions:
Number of active agents act in territory that, by following own “selfish” aims, change the use of the territory. The strategic goal of agents is to maximize their own utility (“satisfaction”).
The development value of land can be menaced by mutual incompatibility of neighboring land-use activities, inconvenient or nonexistent access to infrastructure and inconvenient scale of functional zones and urban tissue.
Regulatory planning has considerable impact on the development of territory by imposing limits and regulations.
Apart from the regulatory planning, the territorial development is influenced by the investment in infrastructure: transport, utilities, facilities and by provision of services.
Any change of use is conditioned by spending transition costs – demolition, construction, new infrastructures, negotiation on releasing of limits or regulations.

Discussion
The model intentionally abstracts from the non-spatial economic principles and it focuses explicitly on the effects resulting from spatial location and functional compatibilities of the cells. Therefore the model cannot be considered a classical economic model that derives the value from the land yields.
The model is build to represent development processes on the level of local urban communities with population between 10 000 – 25000 people. On that scale most factors that determine localization are exogenous to the simulated system and therefore they must be set in arbitrary way. That means that the user must supply expected amount of each type of land uses for each model run cycle (year). In this way the user can test the impact of inputs on resulting land-use pattern.
The main theme of urban communities is their urban growth and the quality and accessibility of services in the area. Therefore the model focuses mainly on the localization of residential, mixed residential and commercial land-uses.

2.2 Assumptions on the agents and their decision-making

- Activities of each agent are limited to single territorial unit: “cells” (agents can be described as cell-based agents).
- Each agent prefers the use of its land that maximizes its satisfaction.

- The satisfaction of agents is derived from the land-use of its cell, from the character of the surrounding land use, number of inhabitants in the neighborhood and accessibility to public infrastructures.

The model follows very simplified assumptions on the homogenous preference structure of all agents in the territory. The agents share the preferences to various combinations of adjacent land-uses, to the accessibility of services, public infrastructure and transportation.

Decision making of the agents must take into consideration various limits that are external to them: the land-use spatial limits and regulations resulting from the territorial plan, existing land use of adjacent "cells".

The model assumes that the decision-making of the individual agents is influenced only by the past decisions of other agents, but not by their concurrent decisions. The inter-agent coordination of the decisions does not exist.

Discussion

The model uses the agents that are immobile, with single agent attached to single cell. Fixing the agent to specific location is typical only for cell-based agent models, unlike free agent models that separate the agents from the specific location. The free-agent models allow the modelers to imitate various mechanisms of agents' interactions: land, housing, labour or commodity market[3]. Some of these models are using several types of decision-makers to represent multiple interests and roles[4]. Disaggregation of the agents into groups can better represent socioeconomical characteristics of simulated population.

The only drawback of the free-agent models is the immense complexity of agents' interrelations. In our case, the purpose of the model is not to locate employment and production activities (industry and agriculture), but to localize the residential use and the activities that would serve the residents. We can therefore accept simplified assumption that the land is used rather as consumption commodity than production factor. The assumptions of prevailing residential use and of homogenous agents in the area cause that we do not need to represent the land and housing market explicitly. By considering the factors of production localization to be exogenous to the modeled area, we do not need to consider the land as the only production factor (besides the capital and wages) and there is no need to simulate the trade and accumulation of land for the purposes of production.

The decision-making on the level of individual agent takes into consideration the potential use that brings the maximum individual "satisfaction" of a cell at minimum transition cost. The decision-making on the level of individual agent ignores the factors of uncertainty connected to the time of transformation and it also neglects the risks of unexpected change of adjacent cells caused by uncoordinated decision-making on the level of individual cells. At the end of the decision process on the level of an individual cell, the partial evaluations of each factor are combined into overall "satisfaction" of the cell.

Not all preferences can immediately result in change of the land-use. Each change of land use requires resources that are scarce (land, public infrastructure). Therefore on the municipality level (model area) the agents are competing for the resources and only the agents with preferences that lead to the highest growth of satisfaction compared to resources will achieve fulfillment of their preferences. The amount of land use changes is limited by the exogenous demand for particular functions (the demand is defined by the user as annual supply of land designated for certain land use). Endogenous limiting factors can cause that the exogenous demand for the localization of certain land-uses may not be fully satisfied. The endogenous limiting factors are:

[3] A well known example of such model is the UrbanSim.

[4] For example the UrbanSim is using three types of agents: households, business and developers.

- disponible developable land determined by the protection zones and buffers and planning regulations;
- the readiness of public infrastructure (or the amount of investment into public infrastructure);

The endogenous factors cause that on the municipality level (model area) only some agents' decisions are going to be realized.

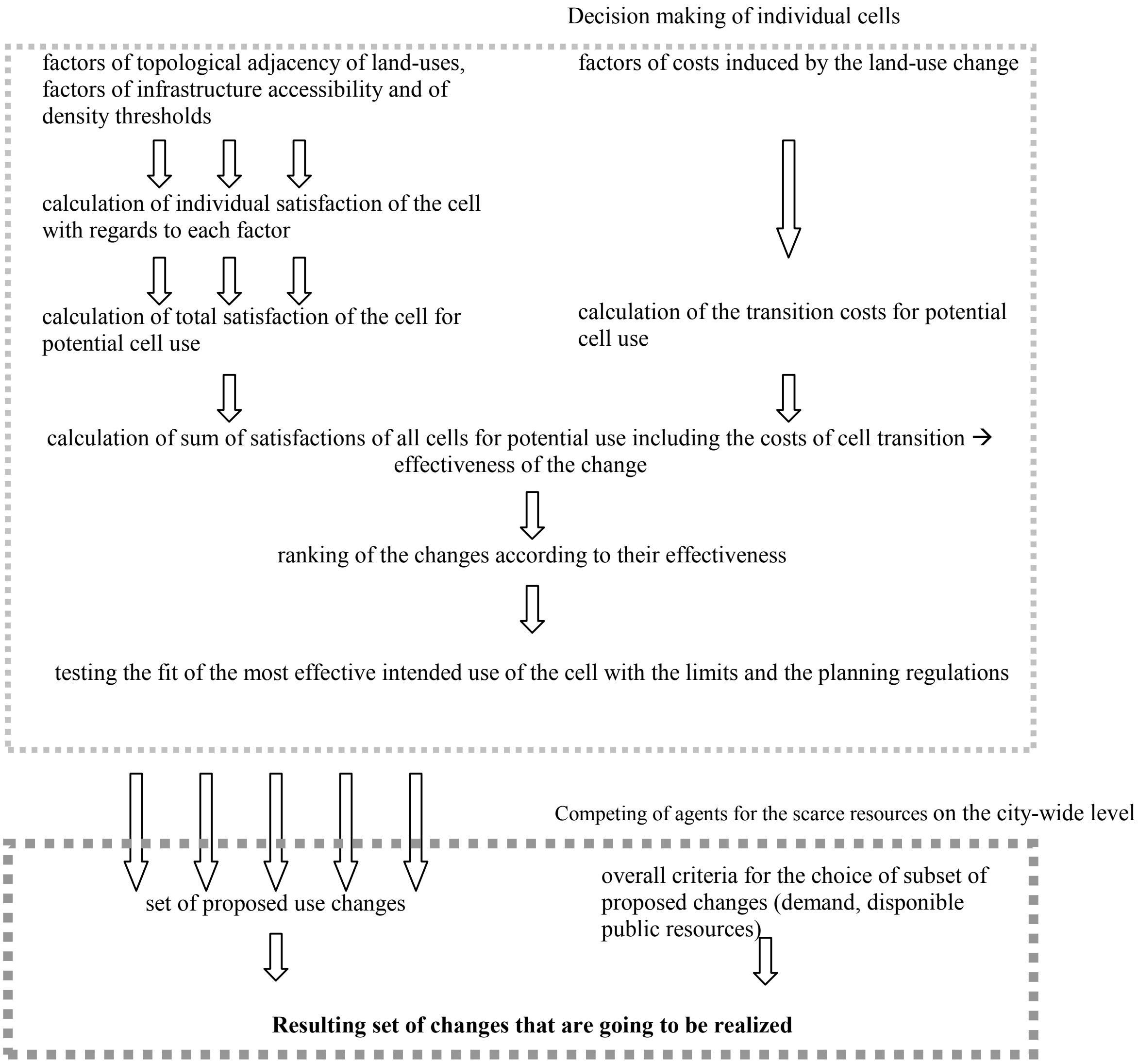


Figure 1. Mechanism of the agent decision process

2.3 Assumption on the succession of land development

We assume the logical sequence of the land-use localization. The initial localization of new residences serves as impetus for the localization of other land uses.

Discussion

At the start of each model cycle (year), the agents decide whether to use their land (cells) for residential use. Their decision is based on accessibility of services and transportation as well

as on the compatibility of the potential residential land-use with the already existing land use of the neighbouring cells. The decision to change the land-use is subsequently realized starting from the cell that has the best satisfaction/cost ratio through the cell with the second best ratio, as long as the exogenous demand for the housing has not been satisfied or endogenous limits have not been reached (accessible public infrastructure, disponible public resources or developable land). The localization of residential uses proceeds simultaneously with the localization of manufacturing land uses. The amount of manufacturing development is exogenously determined for each model run. As a residence-to-manufacturing ratio the manufacturing and residential land-uses do not compete with each other as these land-uses vary in their accessibility requirements and sensitivity to adjacent land uses.
When the number of inhabitants in newly developed (or redeveloped) areas overpasses a certain threshold level, new commercial services serving the inhabitants are supplied. Basic commercial services will mix with residential uses in single cell as they provide the basic services exclusively for that cell. Higher-rank commercial services will localize in the locality (cell) that is best accessible from all residential cells in the area. Similar logics is followed when locating the public services. The allocation of the space for commercial and public services is normatively derived from the number of inhabitants. For basic services the number of inhabitants in the adjacent area is decisive, for the higher-rank services the number of inhabitants in all the respective area is important.

3 Factor of development in the model

The model assumes that the localization of uses is determined by the following factors:

- the functional compatibility of neighbouring land-uses;
- threshold density;
- infrastructure accessibility;
- land-use limits and regulations of the local plan;
- costs of transformation from one land-use to another one.

3.1 Factors of the functional compatibility of land-uses

Mutual effects of neighbouring cells are modeled by using the “cellular automata”. The cellular automaton is based on the grid of cells where each cell can have finite number of discreet states. In the case of the model, each cell represents 75 x 75 meters square. Each cell can have one of 37 states that represent particular land uses. Each cell has one owner (agent).
The use of each cell is determined by the uses of the neighbouring cells. The 9x9 Moore neighborhood is used with each cell having eight neighbours. Mutual effects of neighbours can be positive or negative and symmetric or asymmetric. For example the negative effect of manufacturing use on residential use is not the same as the effect in the opposite direction.
The mutual effects (interactions) of various combinations of neighbouring uses are declared in the form of matrix. The value of each interaction sumarises various factors: physical interference caused by mutual proximity, logic relations between the uses, the psychological and social impacts of the uses.
The mutual compatibility of same or different uses results from the following principles:

- The concentration of mixed uses in central district is caused by the agglomeration economy and other effects of spatial concentration (for example the advantages of multi-purpose trips).
- Basic services and shops are located so that the inhabitants should be provided with reasonably comfortable access.

- Residential uses benefit from adjacency to green areas and open landscape.
- Mixed uses of central districts are ambivalent to green areas. On one hand the green areas make the public space attractive, on the other hand green areas occupy valuable space. Therefore the model classifies the relation of mixed-use central districts and green as neutral.
- Various types of green areas in the open landscape are neutral each to other.
- Spatially separated monofunctional areals diminish the quality of residential zones in their vicinity mainly because they diminish the accessibility and the penetrability of the surrounding area.
- Monofunctional areals in central districts are pushed out by the zones of mixed uses that benefit from the mutual compatibility and attractivity for the customers.
- Hotel services and offices concentrate a large number of people who in turn generate demand for higher-order services located in central district. Therefore, hotels and offices in small grain contribute to viable, lovely centres. However this is not the case of monofunctional hotel and office areals as well as industrial areals.
- Mixed and residential use is not compatible with technical utility areas. The reasons are: risk of pollution, degradation of visual quality of environment and high value of alternative land uses.
- Manufacturing has neutral or positive relations with regards to technical infrastructure.
- Other, unlisted interactions are considered to be mutually neutral.

3.2 Threshold density factors

Shops and services require a minimum number of customers. In the case of basic services it is important that enough customers reside within walking distance by achieving a threshold density. The basic services can be located in residential zones without any negative effects on the neighbourhood. Consequently the use of a cell will change from „residential only“ to „general residential“ when the local residential density has reached certain threshold.
The high-rank services that serve whole area are located in the centre of built-up area. Several services located next to each other form the mixed-use zones of the size that is derived from the total number of inhabitants in the whole territory.

3.3 Factors of infrastructure accessibility

The choice of the optimal use for each cell depends on the location of the cell with regards to public infrastructure:

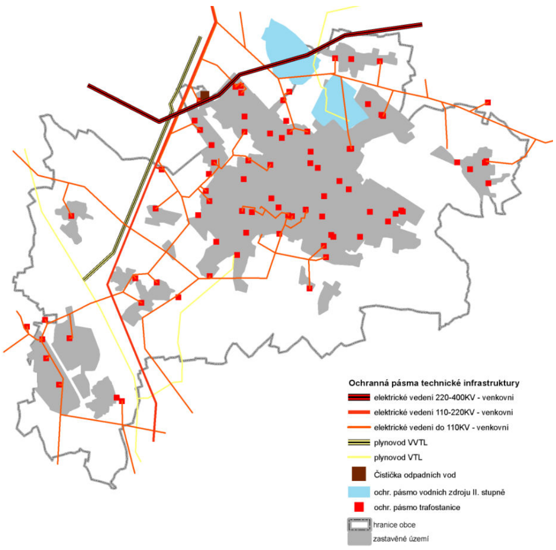
- public transport hubs of regional importance;
- public transport stops of local importance;
- road network of regional importance;
- ports or airports;
- schools;
- policing, fire protection end emergency services;
- barriers (railways, highways, motorways);

Each land-use has specific sensitivity to the accessibility of particular type of infrastructure, therefore the “satisfaction” from infrastructure accessibility depends on the use of the cell.
The model considers the accessibility of the infrastructure outside of jurisdiction fo the municipality as constant for all agents (cells).

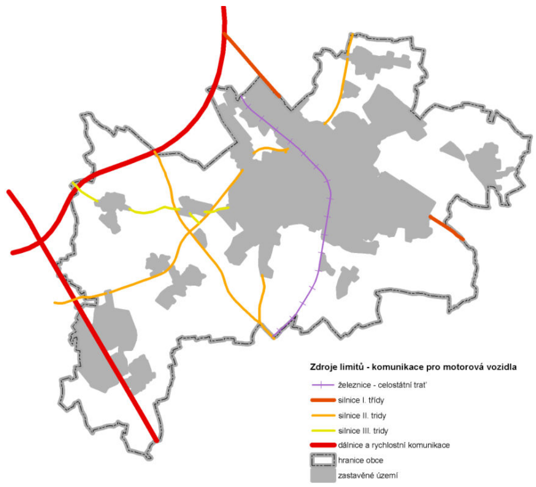
3.4 Factors of land-use limits and plan regulations

Each cell independently decides on its transition from one use to another according to the transition costs and agents' preferences. In this way the dynamics of changes in territory simulated is spontaneous that means it is based on many concurrent decisions of individual agents. However the decision-making of individual agents is also, as in real life, influenced by limits and regulations. The aim of the limits and regulations is to protect the common values and public interest. The model considers 71 legally binding limits and regulations.

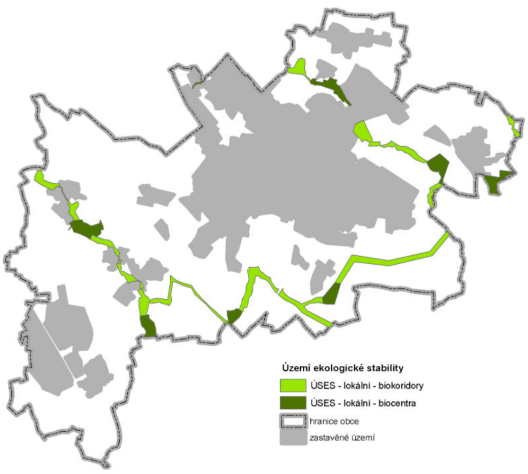
buffers of utilities



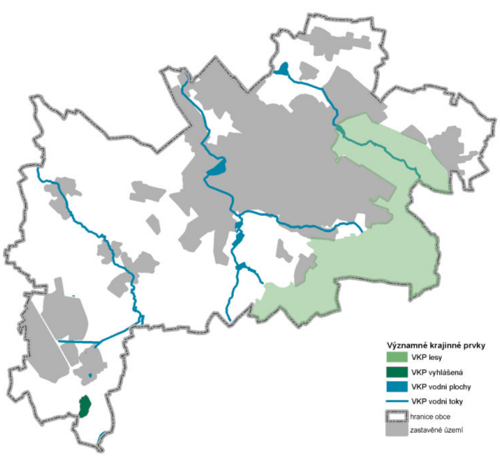
buffers of roads and railways



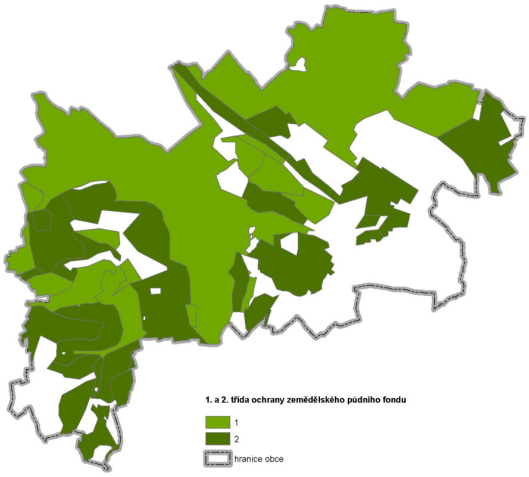
buffers of general nature protection
buffers of special nature protection



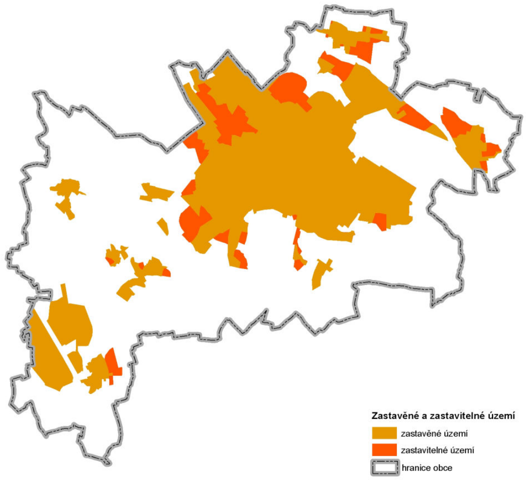
forest zones
protection of underground and surface water.



protection of agricultural land



existing built-up areas and development sites



mining, mineral resources and geology
protective zones
natural heritage protection
buffers serving the waste treatment facilities

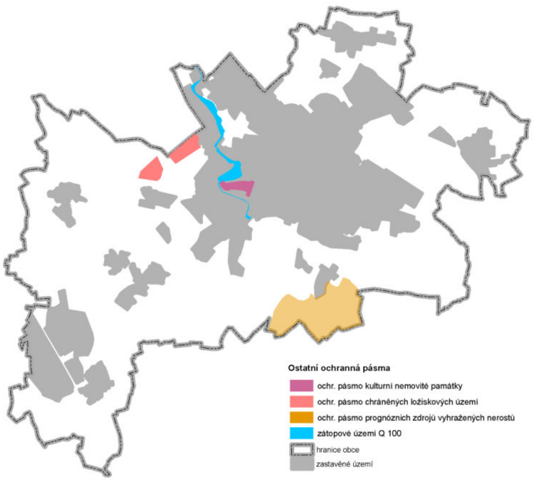


Figure 2: The hierarchical model of the attributes critical for evaluation and choice of living environment

The model evaluates whether the desirable use of the cell by the agent is conform to the limits and regulations.

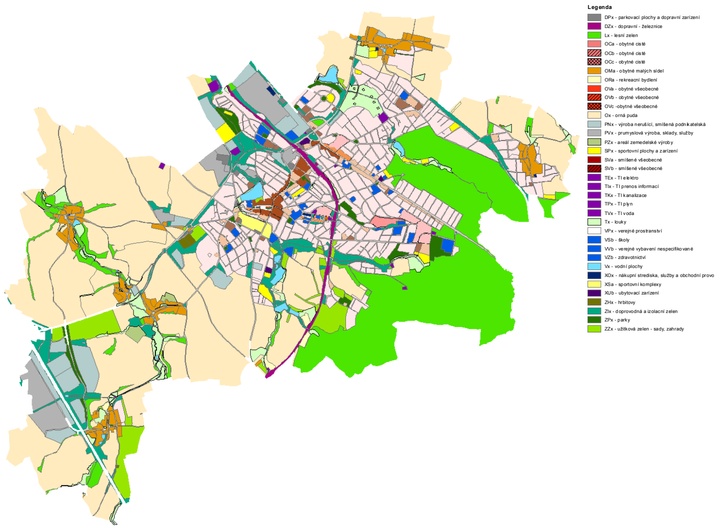


Figure 3: The land-use regulations prescribed by territorial plan

The model enables to confront the decision-making of individual agents with the user-defined limits and regulations. By trial and error process of generating and evaluating the alternative scenarios, the user of the model can also find the optimum degree of regulation.

3.5 Factors of transformation costs

The transformation costs include the demolition costs, costs of new infrastructure and construction costs. If the intended use of the cell violates one or more of land-use limits or regulations, additional costs are imposed that reflect the risk of building ban or of the time delay caused by administrative procedures limits or to change the regulations.

4 Inputs and outputs of the model

The initial state of the territory (land-use, location of major infrastructure, thresholds for development, limits and regulations) and the factors that will influence the future development of land-use are defined by the user "externally". The user also inputs local shared values and preferences by selecting the priority of environmental, economical and social preferences. The output of the model includes the set of scenarios that presents alternative ways of land-use allocation and possibly the future density and the share among greenfields development, brownfield redevelopment and intensification. The scenarios can be confronted with each other on the base of quantitative and qualitative criteria.

Quantitative judgment is possible based on numeric indicators:

- amount of total "satisfaction" change (functional fit);
- amount of "satisfaction" change coming out of total functional fit;
- amount of public expenditures and their impact on the total "satisfaction" (effectivity of public expenditures);
- cost of overcoming the development thresholds of future development;

Based on the outputs presented it is possible to make the assessment to what degree the public investment in infrastructure as well as land-use limits and regulations influence the dynamics of land-use changes.

Visualization is crucial for the qualitative assessment of the overall configuration of built-up areas as well as the spatial relation of built-up area to open landscape. Represented in scenario maps, the visualization makes it possible to judge the outcoming spatial configuration of functional zones, built-up areas, the size and configuration of monofunctional clusters. This will allow the user to confront the input criteria and values with the resulted pattern created by the model.

5 Model validity limits and the questions of model calibration

The model validity is based on the correspondence of the modeled processes with the real world processes. It is possible to decompose each model process on single variables, their states and the transaction rules.
The value criteria that are implanted into the model correspond to the values of selected groups of experts (expert focus group): thus the values express the consensus of model authors. It is intended to verify these inserted values by representative sample of respondents.
It is not possible to verify the correspondence of model outputs because the scenarios of future development are just hypothetical. Also at this moment it is difficult to assess the predictive power of the model. In future the historical data can be used for the assessment of the predictive power of the model.
Apart from the objective description of the factors (land-uses, limits, planning regulations, transformation costs) the model uses also the subjective information inserted by the authors of the model as well as model users. The model keeps the processes transparent and it distinguishes the transactions that are based on descriptive and normative knowledge.
The calibration method follows the division of the processes. The calibration is made on the level of partial processes first. It is much easier to verify the correspondence of the model performance to clearly defined characteristics of the environment than to analyze the reasons of discordance of the model behavior including all factors at once.

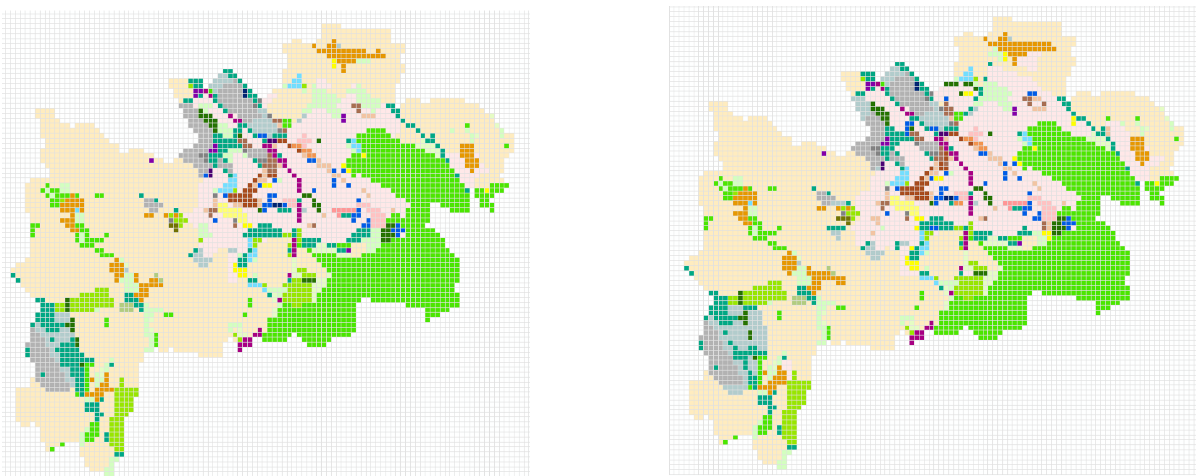


Figure 4: The example of the land-use development limited by planning regulations

6 The use of the model

The simulation model can be used in the domains of education, research, urban planning and management.

In the case of education the model can illustrate the influence of production factors on the future use of territory.
In the field of research the model can serve as standard gauge for comparison of several territories to make general conclusions on the hypothesis validity. The model can be used for the inquiry of factors that are critical for expansion of built-up areas, the verification of effectivity of planning regulations for the attainment of sustainable development of territory or effectivity of public investment into the infrastructure.
In the practice of urban planning the simulation model offers planners to test the impact of alternative urban concepts as well as shared values and preferences of local decision-makers on the development of the territory. The software application of the model offers high accessibility and interactivity that is suitable for presenting of impacts of alternative urban concepts also to public in public hearings.
A user can set the external factors at the start of the running of the model or in the course of the model performance. The user of the tool can control the rate of importance for each of the external factors.

References

1. Beran V., Dlask P.: *Management urdržitelného rozvoje regionů, sídel a obcí (Management of sustainable development of regions, cities and towns)*. Academia Praha, 2005. ISBN 80-200-1201-X
2. Maier K.: *Hospodaření a rozvoj českých měst (Management and development of Czech towns)* Academia Praha, 2005. ISBN 80-200-1245-1
3. Maier K., Vorel J., Jankových V., Vorel O.: Využití informačních technologií pro hodnocení kvality prostředí a participaci uživatelů (Use of ICT for environmental quality assessment and users' participation). *Proměny architektury a urbanismu.* FA ČVUT v Praze: ISBN 80-01-03528X
4. Maier K., Čtyroký J., Vorel J., Drda F.: Udržitelný rozvoj měst a regionů (Sustainable development of cities and regions). *Proměny architektury a urbanismu.* FA ČVUT v Praze: ISBN 80-01-03528X
5. Vorel J.: Learning the public preferences for habitat environment: the use of Conjoint analysis. *Advanced Engineering Design*, June 2006, Praha: ISBN 80-86059-44-8

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