COMPUTER AIDED MANAGEMENT OF WATER & WASTEWATER SYSTEMS IN MUNICIPAL WATERWORKS[1]

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ABSTRACT
In the paper an idea of a computer aided decision support system for the maintenance of water and wastewater objects in communal waterworks is proposed. An innovation of this computer system is the use of mathematical models for computer simulation, optimisation and control of all links composing the complex system of drinking water and wastewater management realised in waterworks. The developed models of a water network and a wastewater treatment plant are described while the possible models for the water pump station and for the wastewater network are only suggested. With the system proposed an active control of waterworks could be done whereas the systems applied up to date in waterworks work without any models. They make only a passive control of waterworks' separated objects, i.e. they try to stabilise the parameters of different processes on the given levels of values. The aim of the paper is to indicate a new direction in the field of computer aided decisions making for maintenance of waterworks.

INTRODUCTION

Water & wastewater system in a city consists of 4 following subsystems maintained usually by one undertaking which is the municipal waterworks: water intake and conditioning station including a pump system supplying the drinking water into the waternet; water network; wastewater network; sewage treatment plant. These 4 subsystems are commonly treated separately as independent units although they create in reality 1 complex system consisting of 4 modules sequentially connected.

This organisation of municipal waterworks has the consequence that all investigation concerning mathematical modelling, optimisation and control of waterworks objects is done for only separate subsystems and independently of one another. Such acting is neither economic nor correct from the control theory's point of view. Each subsystem needs a control. In the intake station, water network and wastewater network (in case of a pressure wastewater network) control of water pumps must be realised while in the sewage treatment plant a water and wastewater pumps control as well as control of air blowers have to be done. The pumps and air blowers are energy consuming devices and to control them the classic error actuated control systems are commonly used that stabilise on a fixed level the values of some process' parameters. (of water level in storage reservoirs or of oxygen concentration in aeration tanks or of recirculation rate of sewage or activated sludge flows in the sewage treatment plant). Such control procedure is often ineffective in case of big and fast changes of extern conditions that affect the water & wastewater processes (changes of the waternet load or of the raw sewage inflow directed onto the sewage plant input). Then the operator of the relevant process tries usually to control it manually changing the controllers' settings according to his experience and these decisions are made separately for each subsystem.. But the control of each subsystem depends essentially on the waternet load which affects the pumps action in the water intake station, the filling and emptying of the retention reservoirs in the water network, the hydraulic load in the wastewater network, and the hydraulic and biological load in the sewage plant. Then a waternet load prediction is an essential element of each subsystem's control.

This way an idea to develop an integrated decision making system for the synchronous maintenance of the whole water & wastewater handling has been arisen and such a system is created on example of the waterworks in Rzeszow which is a city in Poland.

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OBJECT DESCRIPTION – PUMP STATION IN THE WATER INTAKE

The water & wastewater system in the city under investigation is supplied by 2 river intake stations of the yields values of 37.000 m^3/day i 47.500 m^3/day. Both water intakes are equipped with pump systems pumping the water into the waternet and 5 retention reservoirs of the capacities of 1 x 3.600 m^3 and 4 x 3.000 m^3. The entire reservoirs' capacity makes ca. 20% of the productivity of both intake stations and 30% of the water consumption of the city that is 50.000 m^3/day. The filling of the reservoirs occurs now on the base of indications of level sensors, i.e. a reservoir starts to be filled to the maximal level when water volume drops to a fixed minimal level. Such procedure has no relationship with the coming waternet load which is changing permanently according to the day time and year time. While filling a reservoir all pumps in an intake station are started what makes the filling time minimal but does not concern the possible minimisation of the energy costs.

It seems necessary to change the procedure of the reservoirs filling in such a way that the pumps would be activated in dependence on the forecasted waternet load and under consideration of their energy consumption. For the pumps are very energy consuming, then a reduction of the energy costs of only few per cent could make notable savings in the waterworks during the year time. Some problems of this kind are already investigated and in (Waterworth, 2002) an algorithm is discussed to minimize the energy consumption of waterworks pumps by their time distributed switching on and off and under additional consideration of their wear time and the necessary exchange against the new machines. But an implementation of such efficient pump scheduling is possible only when an exact forecast model of the waternet load is known and to develop that model one has to consider the intake station, the water reservoirs and the water network as one integrated water system.

OBJECT DESCRIPTION – WATER NETWORK

Rzeszow city owns ca. 160.000 inhabitants and its water network is 545 km long, from which 50 km is the length of the water mains, 274 km is the length of the distribution network and 221 km is the length of the terminal lines. The communal water network includes 21 intermediate pumping (*hydrophore*) stations and 12.200 collective end users and the structure of the waternet consists in 80% of the rings. The present-day load of the waternet makes ca. 56% of its nominal efficiency and the reason of the load reduction is a decrease of the water demand by the industrial plants. Consequently the waternet is mainly loaded by individual households. For a waternet part of ca. 10% of the whole a computer aided system for making decisions by the water network operator has been developed that consists of a numerical map, a branch data base, a monitoring system and a hydraulic model (Studzinski et al., 2001).

To develop the numerical map of the waternet a specialised software for making digital charts (GIS) has been bought and the waternet map was made using the digitised geodetic charts of the city. The standard software called Geomedia of the firm Intergraph was purchased and it had to be fitted to the waterworks demands. A numerical map consists of the waternet graph and the descriptive data base and it makes a right diagram of a real water network if all characteristic network elements are marked at the picture and all parameters of these elements (attributes) are defined in the data base. By developing the numerical map the structure of the data base, i.e. the water network objects and their attributes, had to be defined. The objects of the branch data base formulated for the waterworks in Rzeszow are following: water lines, pump and intermediate pumping stations, water reservoirs, water terminals, gate valves, reducing valves and check valves, and their attributes are: lengths and diameters of the lines, operating characteristics of the pumps and of all kinds of valves, reservoir dimensions.

The branch data base supports the action of all programs creating the computer aided decision making system. With the structure defined above it makes possible the visualisation of the waternet in form of the numerical map but it does not allow any co-operation between the map and some extern applications, especially the monitoring and the hydraulic model, for it does not include the objects which are appearing there. These objects are waternet nodes which do not appear on the geodetic charts. This way the nodes and their attributes had to be defined additionally. The main waternet nodes are following: water sources, end users, mounting nodes and measurement nodes, and their attributes are water pressures and water demands of the end users. The numerical map of a waternet created using the digitised geodetic charts not only lacks the nodes but it is also topologically incorrect for it is discontinuous. Because of that no hydraulic calculations can be done on the base of that map. To make these calculations possible one has to attach to the standard software Geomedia a nodes generator and also a macro to make the network graph continuous. Only with these programs added a standard GIS software becomes an branch application for creating numerical maps of water networks. After these improvements 3 layers of the numerical map can be generated by the transformed Geomedia software: geodetic layer on the base of the digitised geodetic charts, topologic layer made from the geodetic one after the topology of the waternet graph is checked and corrected, and hydraulic layer made from the topologic one after the waternet nodes are introduced. The latter layer is a base for making hydraulic calculations of the water network.

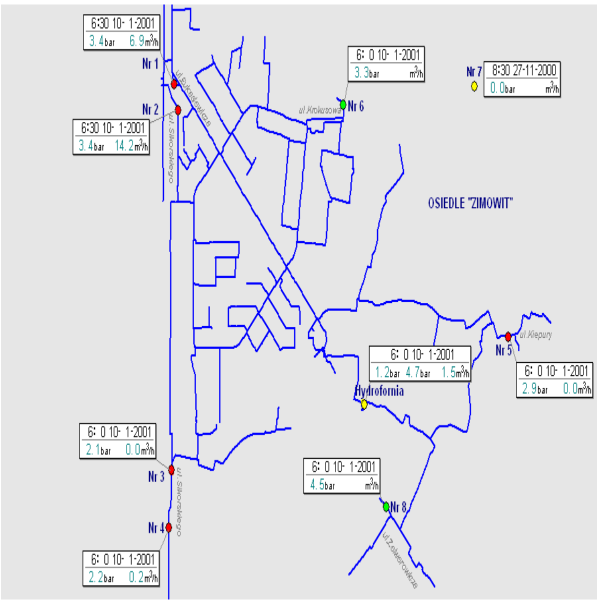

Figure 1. Diagram of the water network investigated.

To make the hydraulic calculations of the waternet a special modelling program has been developed. There the Cross method for solving nonlinear algebraic equations describing the waternet rings is used and such waternet objects as water lines without and with segmental consumption, water lines without and with gate valves, reducing valves and check valves, source nodes like pump stations and water reservoirs, mounting nodes, take off nodes and hydrophore nodes are considered. The modelling program is written in Delphi language and has own graphical editor which makes able creation of separated waternet graphs apart from the numerical map. The data concerning the structure of the waternet and its parameters and used by the program are delivered from the numerical map with help of special buffer files that are generated by the hydraulic layer of the numerical map. The program developed makes the hydraulic calculations statically using daily average water demands or dynamically with help of hourly demand characteristics defined for all days of one year.

To verificate results of hydraulic calculations a monitoring system has been applied in the water network. To run the system 9 measurements points were defined in the waternet part investigated which consists of 2 pressure zones divided by a hydrophore station. The monitoring system works with a standard software for data processing and visualisation that was adopted for the waterworks needs. Transmission of the data from the measurements points placed in the waternet to the computer with the visualisation program installed occurs with help of the GSM telephony. This solution is innovative and reliable in case of waterworks monitoring systems. The main tasks of the monitoring system are calibration and permanent verification of the waternet hydraulic model as well as preparation and verification of hourly characteristics of water demand which serve for forecasting the waternet load.

The above described software modules, i.e. the GIS program, the branch data base, the monitoring system and the hydraulic model of the water network, have been subsequently combined into an integrated computer system that is shown in Figure 2. The main modules of the computer system communicate each other using the data collected in the branch data base.

The computer system works within a net consisting of seven computers in which three computers are used for generating the numerical map and keeping the branch data base, two computers are used for the maintenance of the monitoring system and the last two computers are used for making the calculations of the hydraulic model and the optimization program.

During testing the tool programs of the system that have been developed for solving the technical functions realized in the waterworks, it appeared that some additional program modules performing the managing functions, would be either useful for the whole system and could be integrated into its structure. These are the following preferable modules (applications) with managing functions (see Figure 2):

- WT Application – program for issuing the technological guidelines defined by the development and modernization of the waternet
- OT Application – program for technical testing and passing of the new constructed waternet parts, which co-operates with WT Application
- AW Application – program for maintenance of the waternet break-downs

- ZB Application – program for maintenance of the drinking water demands, production and distribution
- Other Application – office software.

These additional applications use the data that are collected in the branch data base of the computer system already developed and on the other hand they use the data that are useful for the programs realizing the technical functions. In this way it seems to be natural that a computer system created to support the decisions making in the waterworks shall contain the modules realizing both the technical and non-technical functions and the co-operation among these modules shall go on using the common branch data base. Unfortunately such the solution is not used now by introducing the computer systems into the waterworks and the common way is to develop the separated systems for each kind of the functions, either technical or non-technical ones. Our try that we have undertaken in Rzeszow is to overcome this ineffective habit.

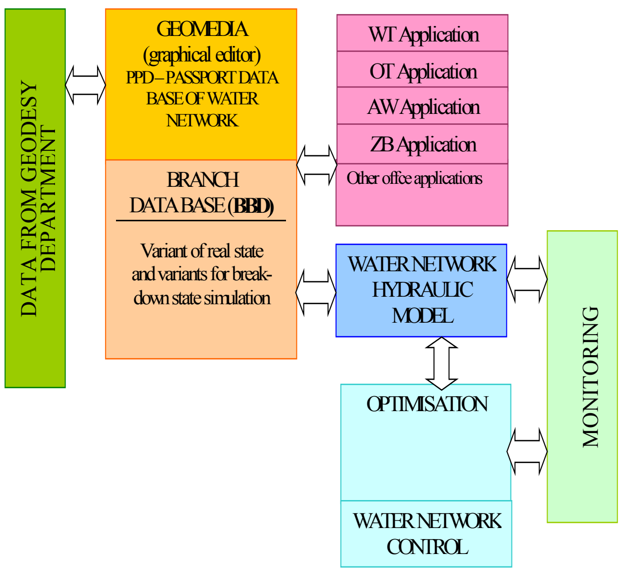

Figure 2. Architecture of the computer system for the water network management.

OBJECT DESCRIPTION – WASTEWATER NETWORK

The wastewater network in Rzeszow is of the mixed kind for it transports the municipal wastes as well as the rain-water. The whole network has the length of 414 km where the sanitary lines make 245 km and the rain water lines make the remaining 169 km. The waste transport in the network occurs gravitationally. The waste composition and the load of the waste network change in cycles according to the changes occurring in the waternet. Up to day there is no large experience in mathematical modelling and optimisation of the wastewaternets that despite some likeness are considerably different from the waternets. The main differences between the both kinds of networks are:

- A wastewaternet consists mainly of the gravitational lines that are not included in a waternet.
- For the nodes of a wastewaternet there is not every time true that the sum of wastes coming into and flowing out of a node equals to zero as it true for a waternet (similarly to I Kirchhoff's law in electrotechnics). The nodes of a wastewaternet are very often in form of tanks where the wastes are collected until their volume achieves a fixed level and only then they are pumped out of the node.
- A wastewaternet has usually a tree structure and not a ring shaped structure like a waternet.

But a hydraulic model of a wastewaternet can be very helpful by calculating and forecasting the hydraulic load of a sewage plant situated on the wastewaternet output and as a result by calculation of the plant controls. Some applicable wastewaternet models are already formulated and tested by the solution of some optimisation and planing tasks (Wedel K., 1998) and there is possible to use this experience by developing a computer aided system to maintain of the whole water and wastewater system in a city.

OBJECT DESCRIPTION – SEWAGE TREATMENT PLANT

In Figure 3 a view of the investigated sewage treatment plant in Rzeszow is shown and it consists of the following objects: raw sewage way, primary clarifiers, aeration tanks containing the activated sludge, air blowing station pumping the air into the aeration tanks, secondary clarifiers, extern recirculation system conducting the activated sludge from the secondary clarifiers into the aeration tanks, outlet of the overplus activated sludge, outlet of the wastewater clarified.

The wastewater treatment realised in the plant consists of the following stages: gravitational sedimentation of solids and organic molecules in the primary clarifiers; biological decomposition of the carbon compounds and the ammonia (*ammonia is changed into nitrites and then nitrites are changed into nitrates*) in the aeration tanks under the aerobic (*oxygen rich*) conditions; gravitational clarifying of the wastewater in the secondary clarifiers.

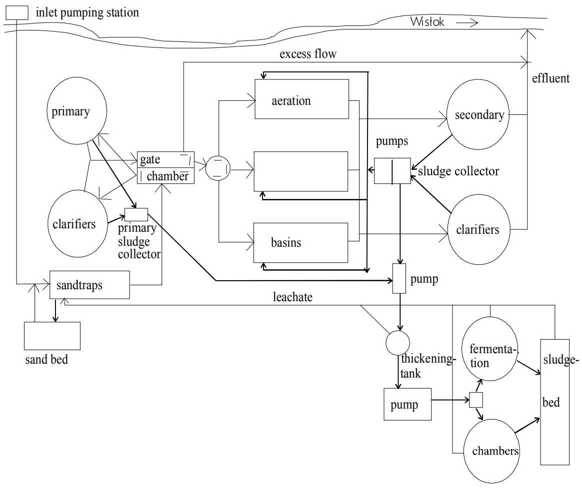

Figure 3. Diagram of the sewage treatment plant.

For this sewage plant a computer aided system supporting decisions of the plant operator has been developed. The system has a modular structure and its functional modules realise differentiated and specialised tasks as follows: the data from the sewage purification process are measured online, in part automatically with a monitoring system and in part per hand in a chemical lab; the data are recorded and processed in the branch data base; the expected inflow volumes of the raw sewage and the expected pollution loads in the wastewater are computed using some forecast models and the measurements processed; the controls for running the process are determined using a control model and the inflow and loads values computed; the controls are then verified by the use of a physical model and the subsequent evaluation of the results of simulation; for this verification also some operational models can be used that describe the whole technological process of sewage purification, like the physical model, but they are made with a more primitive mathematical description as the physical model and are more handy in use; after the verification is made successful, the controls are applied to run the process but if the simulation results are not satisfied the controls computed are rejected and the operator runs the process by himself or starts the computer system for looking for new controls. The structure of this system is shown in Figure 4.

The developed physical model of the sewage plant consists of separated submodels of primary clarifiers, aeration tanks and secondary clarifiers, together with the appropriate connections between them realising the extern recirculation system. The submodels describe the ideal mixing of the wastewater occurring in the primary clarifiers and the aerations tanks, the sedimentation processes occurring in the primary and secondary clarifiers and also the biological processes of nitrification arising in the aeration tanks under the aerobic conditions. This way this physical model belongs to the class called Activated Sludge Model No. 1 (Henze et al., 1995). The model was calibrated per hand using the professional experience, i.e. the values of unknown parameter were determined by sequential procedure after some default values of these parameters as first estimates for the simulation were assumed. The differences between calculated and measured output values of the model and of the object, respectively, were then noted, and a stepwise adjustments of kinetic and stoichiometric parameter values were made based on the knowledge and experience of the user (Wanner et al., 1991). Such adjustments were continued until a reasonable match was obtained between the model results and actual observations. The fit of the physical model is satisfactory and in many cases very good. Only in some cases the errors are bigger than few percents (Bogdan et al., 2000).

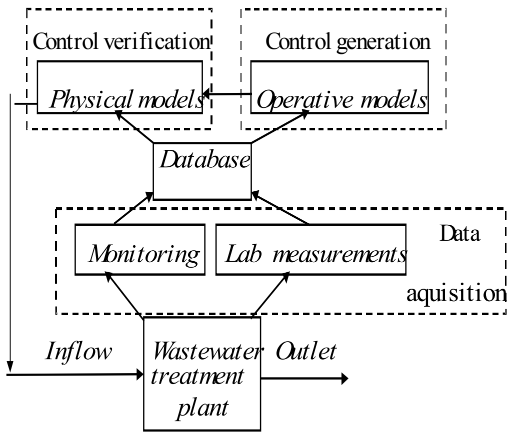

Figure 4. Architecture of the computer system for the wastewater treatment plant management.

The forecast models for the sewage inflow were created in two ways in form of the difference ARMA (*autoregressive moving average*) models and the neural networks. The time of forecasting of the sewage inflow is 1 h. While developing the neural models the same measurement data were used as by the ARMA model. The neural models are of BP (*back propagation*) type. They consist of three layers with 5 neurons on the input layer and with 1 neuron on the output layer and with 7 neurons or 6 neurons on the hidden layer (Studzinski et al., 1998).

The control model is made as a neural model of the whole sewage purification process. To develop this model the data collected in 4 measurement points of the plant were used. These points are: inflow of the raw sewage, aeration tanks, external recirculation system and outflow of the clarified wastewater. In this way the raw and purified sewage parameters as well as the controls of the process have been measured. The data collected are: BOD (*biological oxygen demand*), nitrogen, ammonia, suspension and wastewater inflow on the input of the plant; oxygen and activated sludge concentrations and activated sludge drop ability in the aeration tanks; recirculation flow rate and recirculated sludge concentration in the external recirculation system; BOD, nitrogen, ammonia and suspension on the output of the plant. The oxygen concentration in the aeration tanks and the rate value of the extern recirculation flow are the controls of the sewage plant.

The scope was to determine the output of a real technological process of the wastewater biological treatment for one time-step. The process is nonlinear and such a network was chosen that is capable to handle such nonlinearities. This is a feed-forward (*back propagation*) network with nonlinear transfer functions. The network investigated has three layers (*input - hidden - output*) and each neuron on a layer is connected to each neuron of the next layer. 16 neurons are placed on each the input and hidden layers and 2 neurons are situated on the output layer. The transfer function of the first and second layer is a nonlinear logistic function and the transfer function of the third layer is linear of the type identity. The comparison between the network output and process output is done by a **S**um-Squared **E**rror and this criterion function was minimised with a Gauss-Newton method (*improved by Levenberg-Marquard*). The results of modelling show a very good agreement between the data taken from the sewage plant and the values calculated from the neural model of this plant (Studzinski et al., 1998).

The data used for developing the control model could be also useful to model with the neural nets the whole technological process occurring in the basins of the wastewater plant. This another kind of the model was constructed in such a manner that the input of the plant at time t (*wastewater inflow; BOD, ammonia and suspension concentrations of the raw sewage*), the control sets of the plant at time t (*oxygen concentration in the aeration chambers and recirculation flow*), the output of the plant at time t (*activated sludge concentration and activated sludge drop ability in the aeration chambers; recirculated sludge concentration; BOD, ammonia and suspension concentrations of the sewage purificated*) acted as the input for the network and the output of the plant at time $t+T$ acted as the desired output for the network. This resulted in 12 input parameters and 6 output parameters of the neural net.

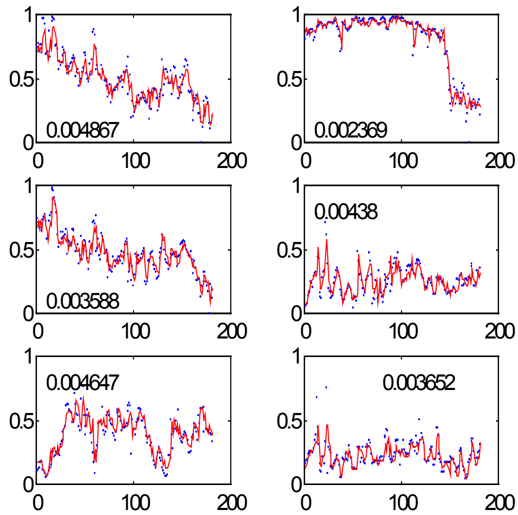

Figure 5. Training the network for six output parameters of the process (*points - data, line - network answer*); the parameters are (*from left to right and from up to down*): activated sludge concentartion and activated sludge drop ability in the aeration chambers, recirculated sludge concentration, ammonia, BOD and suspension concentrations of the sewage purificated (*the numbers within the diagrams mean the least square errors*).

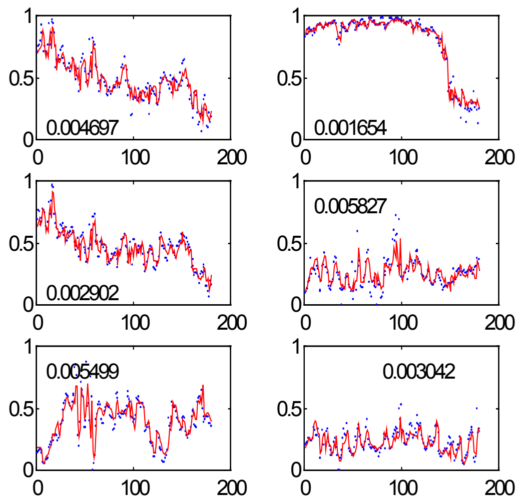

Figure 6. Testing the network for the same process parameters as in Figure 5.

By the development this model we could determine the usability of neural networks for the process under consideration, we could search for important or less important parameters of the process and check the quality of the black-box modelling done by neural networks. That checking was made by the comparison of the neural model with the developed physical model based on the ordinary differential equations.

We have found out that for our real data obtained from the sewage plant a dead time T of one shift gives the best modeling results. We used twelve neurons on the first layer, six neurons on the hidden layer and six neurons on the output one. Using this process model we have obtained the results of estimation of the output of the plant at time $t+T$ that are showed in Figures 5 and 6. We can see from the results the desired correspondence between the real data (*i.e. the object*) and the network (*i.e. the models*).

The conclusion going out from these calculations is that we can replace the physical model by the neural one at the first step of investigation. Then usually quick and not absolutely exact results are desired and the neural models are suitable to achieve this goal. But if more precise results are to be received at the next steps of investigation then the complex and slow but much more exact physical model of the sewage plant has to be used.

CONCLUSIONS

In the paper the main objects of a municipal waterworks have been presented and these objects are the main elements of a computer aided decisions making system that is under consideration. In this system the mathematical models for forecasting the waternet load have the essential function for this load affects the work of pumps in the water intakes, it influences the hydraulic load of the wastewaternet and the treatment arisen in the sewage plant. A correct prediction of the waternet load can minimise the energy consumption in the whole water and wastewater system in a city and to calculate right control algorithms the mathematical models for all objects mentioned are needed. In case of waternets and sewage treatment plants such models have been already developed and calibrated using the real data from the waterworks in Rzeszow and the modelling of intake stations and wastewaternets requires more research. Some works on this topic are already known and this experience could be used. An idea of an integrated computer system for the maintenance of the whole water and wastewater treatment in a city seems to be interesting and very useful.

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