Generative Hydrology Network Analysis

A parametric approach to water infrastructure based urban planning

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Urban water systems need to be dimensioned well to be economical and distribute water in a good quality to all consumers. Their pipe sizes are dependent on demand and location of consuming nodes. Within uncertain development of cities, planning sustainable hydraulic networks is challenging. This paper explores, how the definition of urban design parameters can be supported using parametric urban design models and computational water network analysis. For the latter we developed new components for Grasshopper based on the open accessible water analysis tool EPANET. In two example cases we demonstrate potential applications of this tool for water-sensitive planning of emerging cities to find optimal positions for water sources or pipe diameters. In subsequent research, this could be used to derive probability-based recommendations for the dimensioning of a water network within uncertain growth.

Keywords: water infrastructure, urban planning, parametric design, uncertainty, emerging cities

INTRODUCTION

To create sustainable and resilient cities, it is essential to integrate all kinds of infrastructure into the planning of spatial structures in the best possible manner (Graham and Marvin 2001). Especially emerging cities, such as growing towns and cities in the Global South, are urged to consider infrastructural systems early. But within rapid urbanisation, they need to adapt to unplanned and unexpected directions of growth. Especially the distribution of water, as an essential resource for the prosperity of a city and its inhabitants, requires attention. Focusing on pressurised hydrology networks, this paper therefore describes, how computational tools can assist planners in this process by the integration of water infrastructure analysis methods in a parametric modeling tool. Thereby the issue of uncertainty regarding the growth of emerging cities is considered in particular. We present possible use cases that can rapidly explore the physical limits and hidden chances in the space of possible water distribution system. By generating and analysing urban structures and implementing knowledge from the field of infrastructural engineering as well as of urban planning, we gather
statistics that can serve planners to make recommendations for sustainable water networks.

One challenge in the design of hydrology networks is the determination of suitable pipe dimensions (Grombach et al. 2000). Once set, they have impact on the possible development of cities, since the pipe size has influence on flow velocity, pressure at consuming nodes and water quality. A wide diameter can distribute enough water, but depending on the growth of the surrounding network it might be uneconomical or the flow velocity slows down which leads to aging of water and reduced water quality. On the contrary, a thin diameter might not distribute enough water to its consumers. Normally the issue could be solved easily. If the location and demand of consumers are known, a water network could be planned to facilitate enough pressure at each consuming node. However, the future development of cities can be very uncertain. While some cities grow rapidly, others shrink and with it the location and demand of consumers. Therefore, planning needs to consider different future scenarios. Zischg et al. (2017) have shown, that the EPANET library and generative design can facilitate the rapid exploration of different scenarios. They calculated, how water networks perform in a phased development of a city with the scenarios of decline, growth and stagnation of its population. Their findings show opportunities and weak spots of the planned development and make recommendations for chosen pipe sizes. In this paper we use their work as an example case. By leaving out time-patterns and water quality, we do not analyse the network as thoroughly. However, while Zischg et al. (2017) generate a water network as a subset of a given street layout, we want to show how the street network itself can be generated (and optimised) based on water infrastructural design parameters. Urban structures of emerging cities can grow in uncertain directions. Therefore, street network development might not follow a given plan. By calculating possible growth scenarios, we get a statistical distribution of preferred pipe diameters that could be used to make probabilistic recommendations in the process of growth.

COMPUTATIONAL URBAN PLANNING METHODS
By automating the creation and analysis of scenarios through algorithms, planners can utilise computational resources to calculate a wide range of scenarios very fast. Instead of drawing plans manually, the domain knowledge of the fields of urban planning and infrastructural engineering can be transferred to computational models. In urban planning, computational parametric design has this potential to generate and analyse a large set of design variants very fast (see e.g. Duarte and Beirao 2011; Bielik, Schneider and König 2012; König et al. 2017; Weber et al. 2009). However, hydraulic analysis of the results is mostly conducted in a later stage although it could be easily implemented in the workflow. In the following paragraphs we will show a way to combine parametric design with hydraulic analysis. Thereby, digital representations of existing or future urban settlements are generated as well as the analysis of hydraulic water networks to ensure efficient water flow in these structures be conducted.

Parametric Urban Planning
For urban and regional planning GIS-Software would suit well, since it can handle large datasets. However, it does not have the capabilities for generating designs. We decided to use Rhinoceros (a CAD- and NURBS-modelling software, short: Rhino). Rhino’s advanced geometry-modelling capabilities give enough functionality to draw urban patterns and pipe networks. Through its visual programming language Grasshopper, parametric designs can easily be created. Further on, the community around this software has developed many plugins suitable for architecture and urban planning. Thus, with this setup of software, we can easily create generative models of urban settlements. This means, we e.g. can create digital plans of street networks and buildings that are adaptive to changes of parameters such as density, building typology and size or street profile (Den-
nemark et al. 2017). This allows rapid exploration of a variety of plans.

**Parametric Hydrology analysis**

An existing hydrologic analysis tool is EPANET, an Open-Source library for the analysis of pressurised pipe networks (Rossmann 2000). It was first developed by the United States Environmental Protection Agency USEPA and is now continued by the Open Water Analytics community. It allows the calculation of hydrologic network properties as well as water quality measures based on water demand and topographical location of network nodes. However, currently there is no plugin for Rhino3D/Grasshopper that implements EPANET. Therefore, we extended the Grasshopper tools with components that read and write geometry from and into EPANET input files as well as analyse them. Looking at its structure, it is easy to connect to Grasshopper and parametrise it. It uses text-files that serve as databases for the settings and properties of pipe networks as well as calculation steps and results. It contains sections for network elements like pipes, junctions, tanks, reservoirs or coordinates as well as options for time patterns among others (Rossman 2000). Each text-line in a section defines properties of one of those elements and relates them to each other. A pipe for example is always a line in space with two endpoints. These endpoints are defined in the coordinate section and have an ID. This ID again refers either to a junction, tank, reservoir or emitter and their properties. The setup of such a text-file can become quite elaborate, especially with the integration of time patterns and water quality parameters. For better usability, EPANET is therefore normally used together with a graphical user interface that writes the text-file in the background while the user draws the pipe network. Since Rhino3D/Grasshopper gives us the capabilities of generating the geometry of pipe networks, we only have to write the parameters for each element into the text-file. Through the visual programming interface, we can easily change parameters such as pipe diameters or the position of tanks and consumers and get a direct visual feedback of the performance of the network.

**EPANET-COMPONENTS**

Grasshopper follows a visual programming approach. Algorithms that conduct certain tasks (such as geometry manipulation, calculations or analyses) are represented as components. These components can be connected on the canvas. For our purposes we created a set of such components for water infrastructure analysis (EPANET Components). Currently we implemented three components: writing a hydrology network to a text-file, reading the file and analysing it (see Fig. 1).

**Write Hydrology Network**

The Write-component needs a network of lines as input to define pipes as well as their properties of diameter and roughness. Further on, pipes can be turned into pumps with appropriate settings for strength. For the component to work, points, defining at least one consumer and tank or reservoir are required. Each consumer needs to get a value for the demand and a tank needs to have properties for its filling capacity and volume. If points are not directly connected to the network of lines, their properties are applied on the closest junction in the network. This can be utilised to reduce the lines of a network to save calculation time while considering decreasing accuracy (Walski et al. 2003). With these inputs, the Write-component is able to create a basic EPANET text-file. Since writing of a file with around 500 pipes takes less than 100 milliseconds on our computing system, changing the network of pipes and rewriting it is possible in real-time.

**Read Hydrology Network**

The Read-component is using an existing EPANET input-file to construct a spatial network of pipes, pumps, tanks, consumers and reservoirs in the Rhino3D/Grasshopper environment. It makes use of the library EPANET.dll, which can easily read a well structured input-file. For example, a query can col-
lect data of all pipes and their properties. A pipe has start- and end-node, accordingly a query can collect the coordinates for each node. These can be translated into points in Rhino3D/Grasshopper, which can be connected to a line or even pipe in 3D-space. Similarly, volumes of tanks and position of reservoirs and consumers can be constructed. The component is not restricted to input-files of the Write-component, but can even use other EPANET-files.

**Analyse Hydrology Network**

The Analysis-component needs an EPANET-file. Similar to the Read-component, it queries all network-elements and their properties. Results for pipes can be their flow rate, flow velocity, head loss, actual link status (open or closed), energy expended and pipe roughness or actual speed of pumps. Node properties are their actual demand, hydraulic pressure and pressure. The component also supports time-patterns as long as they are implemented in the input-file. A network of 500 pipes can be analysed with our computing system in less than 30 milliseconds. Combined with the Write-component, both can rapidly analyse networks, making fast exploration of a huge range of networks through e.g. generative design possible. This will be demonstrated in the next section.

**EXAMPLE USE CASE**

In the following we show how the software framework introduced above, can be applied for the planning of cities. The examples thereby used, are reflecting on conditions of uncertain urban growth. Besides our simplified use cases, the analysis of water distribution systems through our software framework of Rhino3D, Grasshopper and EPANET can be extended and applied on other generative principles of urban settlements. Our setup is divided into two parts to show different applications of the components. The first part optimises the location and path of a tank to the consumer. The second part explores growth scenarios to come up with statistical distribution of flow velocity, pressure and pipe diameters by iterating through all possible solutions through a brute-force method.
Optimisation of tank location

To create enough pressure at consuming nodes of a pressurised network, either pumps need to increase the hydraulic head at nodes through use of external energy network or a reservoir or tank need to be placed at a high position to let water accelerate through force of gravity. For simplification, we will only look at the positioning of a tank and its connectivity to the consumer. Normally, the tanks optimal location should be at the highest points of the surrounding terrain, but in consideration of the distance to the consuming node and the slope of the pipe path other networks could perform better. In our Rhino3D/Grasshopper environment, we picked a terrain of 3.5km to 3.5km size and placed one consuming node as a city center in the middle of the terrain to simplify the calculation (see left side of Fig. 2).

A tank can be positioned on this terrain through two parameters. One defines the location in x-direction and the other in y-direction of a cartesian coordinate system. Further on, the shortest possible path from tank to city center is calculated, which will serve as the pipe network. The path is restricted to choose its direction on a grid of interconnected points and chooses only paths that run down slopes. A third parameter defines the minimal steepness a path can take on a slope. A high value leads to serpentine paths and a low value to the fastest, steepest rundown.

With these three parameters we can optimise the location of the tank and the connection to the consuming node in terms of e.g. pressure or costs. We chose to do a one-dimensional optimisation, meaning we only optimise for one factor, namely the maximum pressure. The pressure value can be easily calculated by our Analysis-component. But instead of trying out all options manually, we automated the process using an evolutionary solver (Robinson et al. 2009). Grasshopper there provides a component, namely Galapagos. Our three parameters serve as input for this component and can be seen as a genome. Respectively, the phenom consists of the geometrical representation that is created from the genome such as the tank, node and pipe locations. The evolutionary solver changes the parameters of the genome in several iterations. Each time a phenom is generated its pressure value is calculated. The pressure value serves as the optimisation objective. The evolution-
ary solver tries to maximise it by recombining well performing genomes.

Figure 2 shows how the performance increases throughout 700 iterations. As expected, the best performances were observable at the highest points of the terrain. Accordingly, the evolutionary solver tried to search mainly in those areas for the best solutions. The best performing tank has been chosen for the following setup, in which different growth directions of the city are simulated.

**Exploration of growth scenarios**
Since development of emerging cities can be highly uncertain, the planning of water pipe networks is challenging. By pre-calculating possible growth scenarios, it is possible to derive probabilities for pipe diameters at specific locations. In our setup we calculate a number of possible growth direction from the given city center. Its water source is the optimised tank from the previous example. Since we do not have an existing road network, we use a simple grid as a base structure. The city tries to occupy always a fixed area of this grid by choosing the according number of grid-cells. The cells are chosen by a weighted average of three values: their closeness to the center point, to a thorough road or by their slope. By changing the weights, the city area expands from the center point in the direction of a thorough road or in the direction of the terrain or circularly (see Fig. 3). More scenarios could be calculated e.g. by choosing multiple values for the area of the city or by adding more attractors of growth.

Having a street network, the water network can be subset of it (Karger and Hoffman 2013). A spanning-tree algorithm finds the shortest path from the center point of the city to all remaining nodes of the street network. These nodes serve as consumers, while the shortest paths serve as pipes of the network. An automated calculation, that iteratively increases the pipe diameter for each pipe reaching an uneconomical flow velocity above 2m/s, defines the pipe diameter (Sitzenfrei et al. 2013). This leads to different water networks for each calculated growth scenario.

By recombining the parameters of all three weights through a brute-force method, the pressure values, pipe diameters and flow velocities at each node of the network can be calculated. The results are shown in Fig. 4. The statistical distribution of pipe diameters and pressure give a glimpse on preferable growth directions and could be interpreted in probabilities for the use of pipe-types. Together with the pressure map, which shows where pressure can be more easily maintained, recommendations for decision-making can be derived.

**DISCUSSION AND OUTLOOK**
Zischg et al. (2017) have shown, how generative design of water networks can assist planning in uncertain conditions. A combination of parametric urban design with hydraulic analysis extends the scope even to uncertain development of street networks. We limited our parameters to show the feasibility of the study. Adding more parameters and using different principles for the growth of networks can expand the possible number of scenarios and might lead to more calculation time. Since the Grasshopper environment allows application of more generative design principles, planners can adapt the EPANET-components to their own cases. They could include more parameters, such as preferred or protected areas for development, non-grid-like and partly-looped water networks. However, limitations of the Write-component, such as missing implementation of time-patterns, water-quality or adjustment of other options, currently restrict thorough analysis of water networks. Therefore, the results only work well for cases needing rough approximations.

Further on, this research gathered data on the statistical distribution of pressure values and pipe diameters for growth scenarios through a brute-force method. It could be used to make recommendations for planners by deriving probabilities for preferable dimensioning. By making informed decisions on useful expansion direction of a city with consideration of ideal location of water sources, topography and pre-
ferred land use, pipes could be sized accordingly. The correlation of economic activities with availability of water might lead to an expansion in this direction of water availability (Unesco, 2016), but within uncertainty growth could happen elsewhere, too. By updating the digital model with the physical network, the routine could be newly informed and the preferable development of the water network recalculated continuously to adjust to the new demands.

Lastly, considering the fragility of pressurised water networks under unwanted conditions, emerging cities should not rely on probabilistic scenario building to improve this system. Resilient solutions would provide accompanying alternative water infrastructures that can absorb weaknesses of the pressurised system (Babovic et al. 2017).

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Figure 3
Growth only in road direction (left), growth only considering slope of terrain (center), circular growth (right). By interpolating between these three extremes, more possible growth scenarios are calculated.
Figure 4
Results of all calculated scenarios through brute-force method mapped on the terrain.

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