Parametric Climate Responsive Design

A Tool for Evaluative Site Design

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As its point of departure, this research contends that it must be possible to create a parametric design tool capable of simulating rainwater detention ponds in a 3D model, with a true size, based on relevant parameters. With a focus on site design, a preliminary study shows that it is possible to create a parametric tool capable of automatically calculating and visualising detention ponds. The premise is that the detention ponds must have the required size to store rainwater during heavy rainfall events to avoid flooding further down the hydraulic system. By merging the flexible structure of parametric modeling with the quantitative facts of stormwater management, the tool is able, in the early stages of the design process, to provide the designer with vital information regarding the size of detention ponds required to cope with different rainfall events.

Keywords: *parametric urban design, design evaluation, climate responsive design, site design*

The aim of this paper is to present and discuss preliminary results from the development of a parametric design tool capable of integrating rainwater detention ponds in site design, based on norms and standards from stormwater management. By merging architectural site design with the technical aspects of stormwater management into one platform, the aim of the research is to facilitate the designer's need to instantly evaluate design changes against the hard criteria of rainwater detention. The tool in development focuses on the design and dimensioning of detention ponds on site. The main purpose of on-site detention ponds is to slow down and retain rainwater runoff, in order to avoid sewer system overflow.

When taking climate conditions into account, it is often necessary to evaluate design proposals against a number of hard criteria. This is the case for stormwater management. Such hard criteria may be expressed through mathematical functions, which determine the quantitative performance of the design. In this cross-field between design and calculation, the designer often finds herself evaluating design proposals against quantitative design criteria which, in turn, depend upon specific design scenarios.

Traditionally, design happens in design tools, handled by architects, while technical aspects are evaluated in simulation tools, handled by engineers. This separation creates a gap between the design and the quantitative evaluation against hard criteria. This gap represents an obstacle for the incorporation and interplay between the two professions. It also represents a lag in the design process where moving the design proposal forth and back between different professionals and platforms for evaluation and successive design is a time consuming endeavour. It diminishes the designer's scope for designing *with* quantitative performance criteria rather than *against* them.

VISUAL AND QUANTITATIVE EVALUATION

Due to the versatility of parametric design, it can be put to many different ends. At the urban design scale, however, application has so far been limited, despite its obvious potentials. As urban design is typically one step away from its object (George, 1997), it tends to focus on design principles rather than concrete design of actual objects. The parametric design approach is therefore particularly relevant in urban design, because design principles can be easily translated into rules and parameters. Planning and building code may, in other words, be turned into to computer code (Steinø & Petersen, 2017).

Despite its limited application, at least four different approaches to parametric urban design may be identified. By the first approach, parametrics is used to to provide information for design by relating analytical data parametrically to 3D models. By the se-cond approach, parametrics is used as source of artistic inspiration for novel design. By the third approach, particular needs are addressed analytically through parametrics in the course of design. And by the final approach, parametrics is applied in the form of rule-based design (Steinø et al., 2013).

In this research, we combine the two latter approaches. One the one hand, we aim at developing a tool for parametric site design capable of simulating a wide array of different site layouts in combination with different building envelopes and, ultimately, different facade designs. On the other hand, we seek to integrate quantitative information relevant to the design and location of water detention ponds, based on established calculation rules for their required capacity.

This approach is not fully automated however, as too many relevant parameters are ill-defined. Therefore, the quantitative calculation of detention ponds is to be considered as a form of design aid, helping the human designer to make more informed design decisions while working with the tool. As Beirão et al. (2011) argue, the experienced designer may be able to properly judge the qualities of a design proposal based on partial or incomplete information. But the quality of that judgement can be improved if the system can provide additional information such as density indicators and performance indicators for the design (ibid.).

The ambition of this research is threefold. First, to develop a tool capable of calculating the required size of a detention pond with respect to the catchment area (lot size), the amount of rain (by so-called return periods), and ground cover (buildings, sealed and pervious areas). Second, to visualize the detention pond in a 3D design model. And third, to allow the designer to quickly and easily shift the type and location of the pond according to design criteria.

Based on conversations with urban design practitioners, we believe that such a tool would address important needs for the integration of architectural design with the technical task of dimensioning rainwater detention ponds typically handled by engineers. This, in turn, would facilitate integrated design solutions much needed in urban space design in a time of increasingly extreme weather events.

METHODOLOGY

The parametric design tool described in this paper is semi-automatic in that it assists the user in taking design decisions, rather than taking them for her. As such, it is not an optimization tool as the user has to make the final design judgement not the computer. An optimization tool for the problem at hand - simulate an ideal site design with an integrated detention pond - is not feasible for two reasons. First, optimum solutions to this problem are virtually impossible to formalize. Second, the solution space for a useful tool would be enormous and therefore unfeasible (Scheurer, 2011).

There are basically two approaches to designing a semi-automatic parametric design tool to simulate the size, position and design of detention ponds in site design. While in both approaches, the size of the pond needs to be calculated, it may either be a) generated automatically from user input or b) be adapted by the user through alignment to a calculated value. While approach a) was initially attempted, it turned out to impose too many restrictions to the design scope of the tool to be useful in order to avoid unresolvable loops in the script. Thus, although less elegant but more useful, approach b) was ultimately adopted.

The tool is developed in CityEngine which is a shape grammar-based scripting and modeling environment, in which the computer runs through a list of rules which generate a 3D model. The rules include different parameters which can be changed by adjusting sliders in the user interface. When a parameter is adjusted, the script is re-evaluated and the computer redraws the 3D geometry. Considering that the development of a detention pond basically consists of the five steps described below, these steps can be coded into modular and reusable algorithms. These algorithms can then be varied using the defined parameters and thereby adjusted to the specific design task.

The script is based on the established body of norms and coefficients in stormwater management, and is based on Danish standards for rain intensity (Bentzen, 2014) which are defined as a probability factor expressed as 1, 2, 5, 10 year events or more. Some materials such as green roofs and surface covers provide a latency in rainwater runoff. A set of those have been integrated into the set of tool parameters, based on their evaporation and infiltration specifications (Gou, 2017; Bentzen, 2014; Speak et al., 2013). A select set of geometry in site design has been quantified and its mathematical relations have been defined (see below). Once established, the relevant mathematical relations have been transformed into code.

The code has been adapted with regard to flexibility in the distribution and dimensioning of building envelopes and detention ponds on a site, in order to allow for a wide range of design possibilities. The resulting script has been evaluated and modified through testing against different design scenarios. In addition, an important focus of the research has been to develop a an intelligible and non-technical set of parameters for the tool, in order to make it as user-friendly as possible.

INTEGRATED DESIGN

With the high ratio of sealed surfaces in built-up areas, rainwater has little chances of sinking into the ground or run off through natural waterways. Therefore, measures must be taken to avoid flooding in urban areas. Traditionally, the solution has been to pipe the rainwater away or to store it in tanks (Gibbons, 2017). However, an increased focus on managing surface water, which is the rainwater that falls on any city's surface (ibid.), has resulted in a number of comparable initiatives such as the USA Green infrastructure (GI), Best management practice (BMP), and the UK Sustainable Drainage system (SuDS) (Ashley, 2011). The shared characteristic for the initiatives is that they focus on managing stormwater in alternative ways, compare to the traditional pipe solution.

Due to climate change, the hydrological cycle has changed and more water comes more suddenly, in the form of extreme rainfalls, river flood flows and storm surges (gibbons, 2017). An increasing quantity of water drainage from impervious surfaces in towns and cities result in increased volumes of flow, faster arrival and higher peak flows, causing both environmental and property damage and, more and more frequently, loss of life (Chocat et al, 2007).

In the past, stormwater management has been conducted primarily by engineers and hydrologist, but within the last decades, focus has shifted towards an integrated view of working with stormwater management. In order to deliver integrated sustainable stormwater management, Potter et al. (2011) argue that a close and effective collaboration between "spatial planners" and engineers is of vital importance. For this collaboration to function properly, it is crucial that engineers are included - and interested - from the early stages/start of the project development (ibid.). This view is supported by Cettner et al. (2013) who in a series of interviews observed a clear tendency that the involvement and inclusion of stormwater specialists in the early stages of design development is crucial to a successful implementation of alternatives to the traditional pipe system.

This new focus on alternative forms of stormwater management calls for a closer working relationship between spatial planners and engineers. This collaboration is often complex as the engineers experience that stormwater management often has a low priority among spatial planners, compare to other planning issues (Potter et al, 2011). The incorporation of stormwater management early in the design process, nonetheless, is crucial to the successful incorporation of stormwater management into the design (Cettner et al., 2013).

In order to avoid large mono-functional, technical infrastructures in urban space, stormwater management must be subject to integrated design. Apart from meeting hydrological objectives, such as flow rate, volume, frequency, duration and quality, stormwater management infrastructures should add value to local communities and form useful and aesthetically pleasing landscapes (Echols, 2007).

MATHEMATICAL BASIS

In this research, an important element is the dimensioning of detention ponds, which are central to the management of surface water (Guo, 2017). Detention ponds are used to store rainwater during and after heavy rainfalls and to subsequently direct the rainwater slowly into the sewage system or infiltrate it into the soil (Bentzen, 2014). In principle, three types of detention ponds exist. The first type is the Flood control detention basin (dry basin). The second is the Stormwater retention basin (wet basin). And the third is the Infiltration basin and trench (porous basin) (Guo, 2017).

When modeling small catchment areas less than 150 acres (˜ 60 ha), it is acceptable to assume rain to fall uniformly for runoff volume predictions (Guo, 2017; Bentzen, 2014). In this case, the required storage volume of the pond is equal to the net-flow to the pond - the difference between the inflow and the outflow, in other words - multiplied by the duration of the rain: Vol = (Qin - Qout) * Tr (Bentzen, 2014). Vol [L] is the required volume, Qin [l/s] is the inflow to the pond, Qout [l/s] is the discharge of the pond, and Tr [s] is the rain duration (Bentzen 2014).

The inflow of the pond is determined by the size of the reduced catchment area (Fr) and the rain intensity (i). The reduced catchment area expresses the percentage of a given catchment area which contributes water to the basin (Bentzen, 2014).

The rain intensity is based on rain statistics, which are typically collected by national agencies. Rain statistics are mostly expressed as IDF-curves (Intensity-Duration-Frequency) and are gathered in one equation i = c * trα. i is the rain intensity [l/s/ha], tr is the rain duration [s], c and α are parameters relating to the chosen return period (table 1) (Bentzen, 2014).

Return period T (year)	C	α	Limitation for t_r
20	55600	0.79	20 min - 4 days
10	45960	0.79	20 min - 4 days
5	28070	0.76	15 min - 4 days
2	16290	0.73	15 min - 4 days
1	10980	0.71	15 min - 4 days

Table 1
Danish values for C and a and limitations for rain duration by return period in years (Bentzen, 2014).

The return period is the number of years in which a rainfall of the largest given size is likely to occur once. Return periods are typically given in 1, 2, 5, 10 and 20 years. Dimensioning a detention pond for a return period of e.g. 10 years means that the pond must have the required volume to withhold the water from the largest rainfall event which is likely to occur once during that period.

The outlet is the amount of water seeping out

Figure 1
Scientifically defined parameters for the calculation of the size of detention ponds (Bentzen, 2014).

from the detention pond over time, as the pond is merely delaying the water, not keeping it. It is controlled by the designer and must typically comply either with a large hydrology plan for the whole region, or with regulations. The outlet is typically measured in l/s/ha, and can be assumed to be constant (Bentzen, 2014)

Thus, the dimensioning of a detention pond can be separated into five steps:

1. Determine the size of the catchment area for the detention pond.
2. Determine the reduced catchment area. This is an indication of the share of rainwater which will reach the water system. The reduced catchment area equals the total size of the catchment area multiplied by the runoff coefficient, which is a number between 0 and 1. The runoff coefficient is a result of three parameters; the degree of imperviousness, the degree of connection, and the hydrological reduction factor.
3. Calculate which timespan generates the largest volume of rainwater. Short rainfalls are often intensive. Long ones are often less intensive. To calculate which type produces the largest volume, it is necessary to have access to either local or national rain intensities with corresponding national parameters (Bentzen, 2014).
4. Calculate the required volume. This is done by including the national parameters, the outlet from the detention pond, the reduced catchment area and the calculated timespan.
5. Deciding the appearance and position of the detention pond and visualize it. Placement of the detention pond requires the basic understanding that rainwater will run downwards to the lowest point in the catchment area. The appearance of the detention pond is primarily up to the designer as long as the required volume is achieved.

(1) F_{total} Total catchment area [Ha]

(2) $\beta = \frac{F_{imp}}{F_{total}}$ Degree of imperviousness

$\delta = \frac{F_{connected}}{F_{imp}}$ Degree of connection

$\theta = 0 \text{ to } 1$ Hydrological reduction factor

$\phi = \beta \cdot \delta \cdot \theta$ Runoff coeficient

$F_r = F_{total} \cdot \phi$ Reduced area [Ha]

(3) $t_{r,max} = \left(\frac{-c \cdot (\alpha - 1) \cdot F_r}{Q_{out}} \right)^{1/\alpha}$ Timespan [min]

(4) $Vol = (c \cdot t_r^{-\alpha} \cdot F_r - Q_{out}) \cdot t_r$ Required detention volume [l]

(5) Appearance and position

The different inputs for the calculations have been transferred into the parametric model by dividing them into two categories; user inputs and geometrical inputs. The user inputs are inputs which are controlled by the user and include the return period, the outlet and the type and placement of the pond. The geometrical inputs are data, which are provided by the model itself, such as the size of the reduced catchment area, the constants for the chosen return period and the rain duration.

RESULTS

At the current stage, the tool is able to simulate and visualize both building layouts and detention ponds at different levels of detail. Merging the technical aspect of calculating the required size for a detention pond with the spatial visualization of the proposed design allows the user to quickly integrate the design and layout of detention ponds into site design. The tool allows for the design and positioning of several ponds, in order to offer some design flexibility and to cater for a variety of terrain conditions.

The tool does not propose any optimal solution, and does not automatically propose any optimiza-

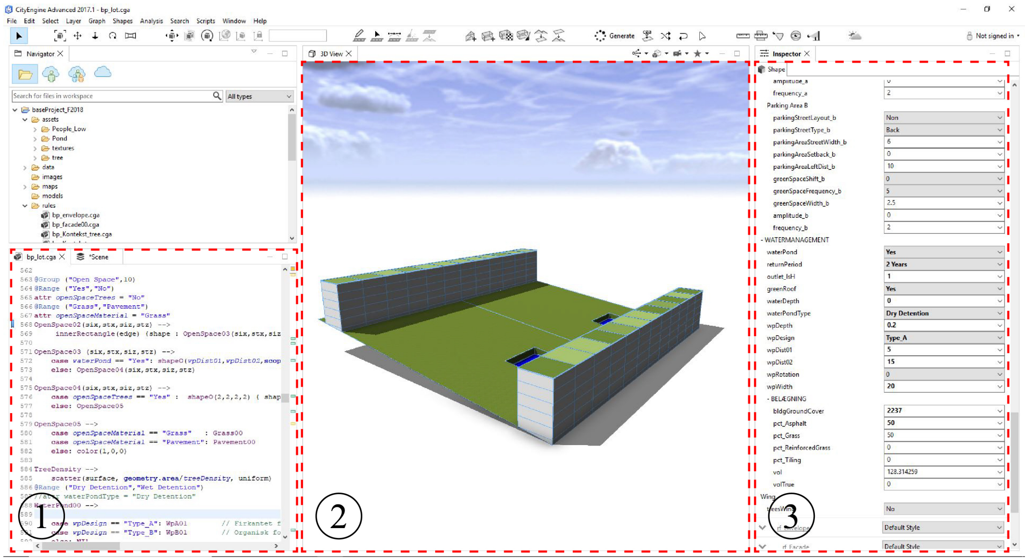

Figure 2
The CityEngine GUI. The main parts are 1) the rule editor, 2) the 3D viewport, and 3) the inspector panel.

tion of a design proposal. Instead, it provides instant visual and numeric feedback which can be used in order to analyze the effects of design changes on the required size of the detention pond. Currently, a rounded and a rectangular pond design may be chosen. The width and depth of the ponds may be set, while the tool automatically calculates the length to match the required volume.

In order to use the tool meaningfully, the user must observe the fact that water flows downwards to the lowest point in the terrain and position the pond(s) accordingly. The tool does not warn the user of meaningless pond positions.

The three main parts of the CityEngine GUI (figure 2) are 1) the rule editor where the code is written/displayed, 2) the 3D viewport showing the model, and 3) the inspector panel where parameters are set. In addition, there is a report tab which reports numeric data from the model. As there is no need to interact with the code, this interface offers an intuitive and easy-to-use way to interact with the tool, even for users without coding skills or technical knowledge of stormwater management.

In the Inspector, the parameters are grouped into calculation parameters and design parameters (Figure 3). The calculation parameters control the size of the pond and comprise return period, outlet, green roofs, and building ground cover (footprints). As the latter results from design parameter settings, it must be fed data from the report tab. As the tool does not currently allow for detailed landscape design, percentages for different ground covers (asphalt, grass, reinforced grass, tiles) may be set for unbuilt spaces.

Appearance parameters control the design and location of the pond(s) and comprise the parameters pond type (wet/dry), pond design (rounded/rectangular), width, and depth. It also comprises the location parameters distance 1 and distance 2 to shift the pond(s) horizontally on the site and rotation to rotate the pond. Further the tool also has parameters for controlling site layout, building envelopes and facades (see Steinø, 2017), which are not presented in the context of this paper.

Figure 3
Inspector panel with control handles controlling calculation and appearance parameters.

Watermanagement	
waterPond	No
Calculation	
returnPeriod	5 Years
outlet_lsH	1
greenRoof	No
bldgGroundCover	0
Surface cover	
pct_Asphalt	50
pct_Grass	50
pct_ReinforcedGrass	0
pct_Tiling	0
Appearance	
waterPondType	Dry Detention
wpDesign	Geometric
wpWidth	15
wpDepth	1
wpDist01	10
wpDist02	10
wpRotation	0
waterDepth	0.8

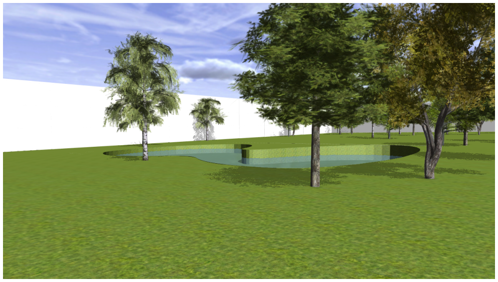

Figure 4

Figure 5
Street level views of site design proposals with rounded dry and wet detention pond designs.

DEMONSTRATION

In its current stage of development, the tool is capable of modeling a site design with building envelopes, ground cover textures, trees and detention ponds. At higher levels of detail, it is capable of modeling volumetric details (setbacks, balconies, roof shapes, etc.) and facade details (walls, openings, parapets, ledges and lesenes) as well as building surface textures (all of which are not shown).

As is the case with CAD software, the model can be visualized in different projections and in perspective view from different viewpoints in real time. This allows for fast and detailed examination of the design, both in overview and close up. Parameters can be adjusted while viewing the model in any projection and from any viewpoint, thus allowing to test the effect of different scenarios both in detail (Figure 4-5) and for the overall design (Figure 6-7).

The combination of street level and bird's eye views of the design proposal allows the designer to analyze the effects of different detention pond designs in fair detail. As an in-depth understanding of the technical and computational bases for dimensioning a detention pond is not required, the tool allows architectural designers with no such knowledge to consider stormwater management at a qualified level in the early stages of design development. It also provides a level of detail suitable to communicate design scenarios to non-design professionals and laypersons.

DISCUSSION

In order to develop a parametric design tool which provides a large freedom of design while at the same time incorporating the necessary hard criteria, a cost/benefit prioritization must be made. At the current stage of development, the parametric design tool includes some parameters and allow a certain freedom in design. As outputs cannot at the same time be inputs (as in the case of building footprints above) without applying optimization, which, in turn, requires an optimum state to be definable (and computer power to be sufficient), choices have to be made.

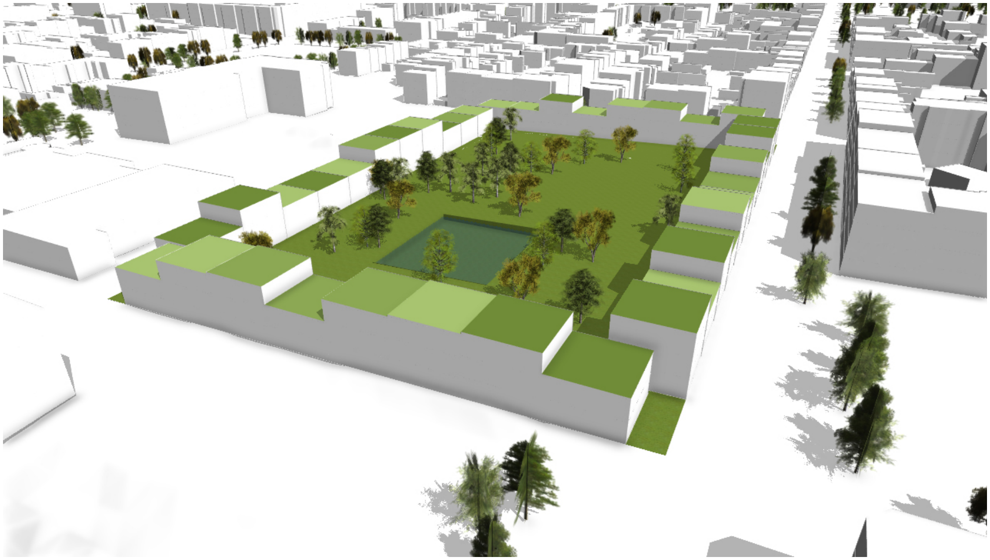

Figure 6
Bird's eye views of site design proposals with rectangular and rounded detention pond.

Figure 7

While this research demonstrates proof of concept, both detail and a shift in priority may be added. As for detail, it would be desirable to allow for more versatile and detailed design than the choice between rounded and rectangular ponds. It would also be desirable to have a definition of ground cover types which is more mathematically precise than estimating percentages. This is complicated however, due to interdependencies which are difficult to code without corrupting the data structure of the script.

As for shift in priority, changing building footprints from output to input would make the model more elegant and fool proof, as no data from the report tab would have to be fed back as an input. But this is tricky, as it limits the freedom of design with regard to other relevant parameters. It might also be worthwhile to explore the scope for integrating topology analysis into the tool, in order to have it automatically suggest meaningful locations for detention ponds.

Finally, the tool has a general limitation in that it bases calculations solely on the site (polygon shape) in question. In real life, watersheds on adjacent areas may cause rainwater to run off onto the site or vice versa, potentially leading to different volumes of water to be catered for. Natural topography (ridges, watersheds) is not the only determinant, as landscaping (curbs, molds, etc.) would also determine the surface flow of rainwater. Nonetheless, integrating topology analysis in combination with volume calculations for adjacent areas might also improve the validity of the tool.

CONCLUSION

With global warming, the increase in number and frequency of extreme weather events requires urban designers to increasingly consider climate responsive design solutions such as rainwater detention ponds. This has traditionally been the domain of stormwater management experts. Most existing design tools are separate from simulation tools. These sets of tools also require specialized knowledge possessed by different professionals. Therefore, design proposal must be moved forth and back between different professionals and platforms. This is time consuming and diminishes the designer's scope for designing *with* quantitative performance criteria rather than *against* them.

A tool which would bridge the gap between urban design and stormwater management would not only facilitate a better integration of stormwater management into urban space design. It would also potentially improve the design quality of stormwater management infrastructures in urban space.

In this paper, we have demonstrated that the technical knowledge and mathematical basis for the construction of such a tool is available and can be integrated into a parametric urban design tool capable of visualizing the size, design and location of rainwater detention ponds in the context of site design with buildings and opens spaces. This can be done at a level of detail which is high enough to make informed design decisions as well as to communicate design scenarios to non-design professio-nals and laypersons.

While there is scope for refinement and shifts in priority, the most mathematically significant parameters such as catchment area, ground cover type, outlet into the sewer system and return period have been integrated into the tool at the current stage of development. Thus, proof of concept has been demonstrated.

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