Multi-objective Optimization of Digital Terrain Models for Climate Adaptation Planning

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Abstract: As part of a joint effort between academia and practice, we propose a novel approach to digital terrain modelling for climate adaptation planning. In contrast to existing workflows, it allows designers to merely describe desired drainage patterns for a given site and use genetic solvers for their subsequent optimization. Leveraging algorithmic strategies opens the possibility to analyse multiple proposed site layouts and identify the most resilient ones. By validating the method on three typical residential development projects, this paper puts renewed emphasis on the importance of terrain modelling in the context of flood protection – a domain often dominated by technical, hardscape solutions.

Keywords: Algorithmic design, climate adaptation planning, terrain modelling, evolutionary solvers

1 Introduction

Climate Adaptation Planning is one of the most significant challenges currently faced by municipalities across the world. The 2021 wave of flood events in central Europe caused by heavy precipitation is only one example of how severe these catastrophic events can be. Within two weeks, more than 240 people died, and the total cost of damage was estimated at $12 billion. Unfortunately, this is not an exception – flooding consistently ranks among the costliest of all natural disasters (HARTMANN et al. 2019). As with any complex phenomenon, there is no universal remedy, but one is clear – water by its nature flows downhill. Hence, strategically shaped topographies can help mitigate the results of future flood events.

While climate adaptation planning frameworks put increasing emphasis on responsive terrain modelling, established CAD workflows still revolve around traditional methods, where explicit user input is required for every elevation point. Human effort associated with managing this complexity often leads to only a few alternative scenarios being analyzed and rarely produces optimal solutions. Instead, we propose leveraging parametric design strategies for automated development, evaluation, and final optimization of resulting terrain models.

Our research expands upon existing investigations into comparable generative design frameworks (KRISH 2011), (AGKATHIDIS 2016) and multi-objective optimization techniques stemming primarily from the field of architecture (WORTMANN & FISCHER 2020). The main contribution of work presented in this paper emerges from applying these principles in a new context. Often, research and its application in the real world are disconnected. The strength of our collaboration lies in a bi-directional exchange between academia and practice, allowing for cutting-edge techniques to find immediate application. In the following chapters, we propose a novel algorithmic terrain modelling technique developed specifically to optimize urban topographies for stormwater management purposes. The suggested workflow consists of a process description for landscape architects involved in climate adaptation planning, a generative method for automatic scenario creation, and a dedicated performance assessment framework.

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2 Terrain Modelling for Climate-adapted Cities

2.1 Process Description

From a flood protection point of view, there are two critical functions which need to be achieved at every site: safe stormwater conveyance and sufficient detention. The latter provides available volume to temporarily store precipitation and – once the rain stops – gradually release it to the environment. The former directs runoff to dedicated detention elements while ensuring that the surrounding infrastructure is unharmed. In urban areas, the above functions are often performed by underground structures such as stormwater canals or storage pipes. Due to economic reasons, however, these elements are dimensioned to perform optimally during statistically most frequent rain events and typically can't handle heavy precipitation associated with less common *cloudburst* occurrences (BARBOSA et al. 2012). Once the underground network reaches its full capacity – or if there is no underground infrastructure at all – stormwater flows along the slope of the terrain. To control this flow in urban settings, road surfaces are often intentionally utilized to convey excess runoff and green areas designed to temporarily store it (DIETZ 2007).

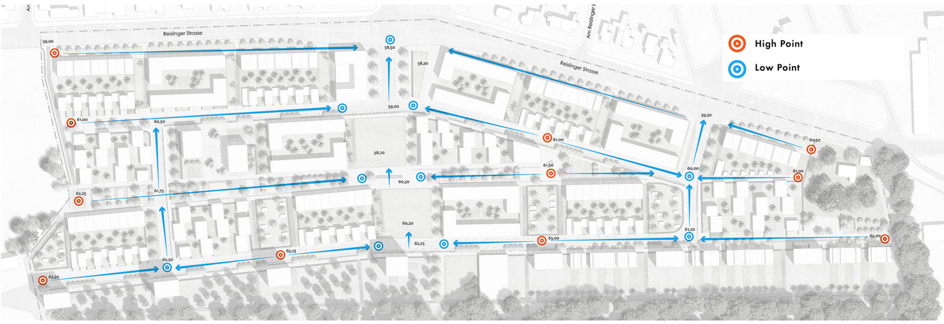

Fig. 1: Example of a conceptual site drainage plan with high & low points, resulting slope directions and dedicated detention areas (© Ramboll Studio Dreiseitl)

Developing resilient flood protection strategies for climate-adapted cities, therefore means designing adequately shaped topographies with close consideration of proposed land use. Flow directions are specified by placing high and low points along the street network and detention volumes provided by locating sunken areas throughout the site (Fig. 1). The process follows a set of constraints, resulting both from the physical characteristics of stormwater flow as well as legal planning requirements. To provide an example: in an urban context, the ideal longitudinal street gradient should fall within the range of 1 to 5%. Lower values result in suboptimal drainage results, while higher impact accessibility and increase the risk of erosion. Detention areas, on the other hand, must provide sufficient volume for a rain event of legally specified intensity and maintain a maximum depth of approx. 60 to 90 cm to reduce the probability of drowning (EKKA et al. 2021). Furthermore, for economic and environmental reasons, the necessary earthworks required to construct any designed landscape should be minimized. This is typically achieved when proposed terrain models closely follow the existing ground.

The development and subsequent optimization of an effective drainage plan can therefore be described as an iterative act of solving against the following criteria:

1) drainage patterns derived from high & low points' distribution,
2) allowed slope range,
3) distribution of detention volumes,
4) cut & fill balance.

Depending on the size and complexity of a given site layout, between a few dozen to a few hundred of elevation points are required to meaningfully describe proposed topography. Consequently, in a typical stormwater management planning workflow, each elevation must be explicitly defined, and the resulting terrain model evaluated against the above-defined assessment criteria. In an iterative process individual points are then adjusted until all design objectives are satisfied. Various CAD tools help in automating and visualizing the analytical part, but they still mostly rely on explicit user-input of elevation data. The approach is mundane, error prone and typically produces only a few design alternatives.

2.2 The Parametric Model

In contrast to direct input of data, generative design is a method where features (such as building elements, or landscape architectural objects) are shaped according to algorithmic processes (LEACH & YUAN 2019). In this planning paradigm, the correlation between design intent and design response is determined by parameters and mathematical formulas. This represents a shift away from explicit manipulation of individual objects towards the more general process of defining rules which enable automatic creation of multiple design options (MENGES & AHLQUIST 2011). In the context of terrain modelling – instead of specifying the exact elevation of a given point, one would describe the *relationships* between neighbors (Fig. 2). Should they be situated higher, lower, or on the same level? Answering this question for all points is analogous to defining surface flow directions and – ultimately – stormwater runoff patterns for the entire site.

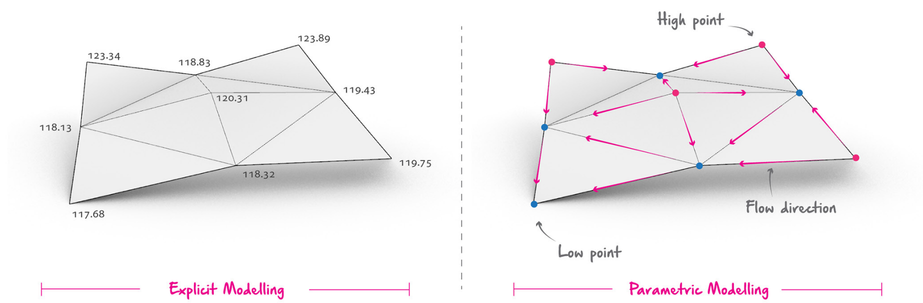

Fig. 2: Schematic differences between explicit and parametric modelling paradigms applied to digital terrain modelling

Such loosely defined parametric model, however, would yield an infinite number of possible design options. To narrow down the solution space, and conform with real-life requirements of landscape architectural projects, additional constraints need to be introduced. One – legally allowed slope range – was already mentioned in the previous chapter. Another – stems from how terrains are constructed. Since all earthworks must happen within the given site boundary, its elevation always remains unchanged. This simple rule *pegs* the outermost points to the existing ground, thus constraining the model further (Fig. 3). Likewise, some projects may necessitate preserving existing elevations in additional areas. This requirement can also be met by pegging the corresponding points to their current elevation. Once fully constrained, such a parametric model can be used to generate multiple design options simply by adjusting individual slope values.

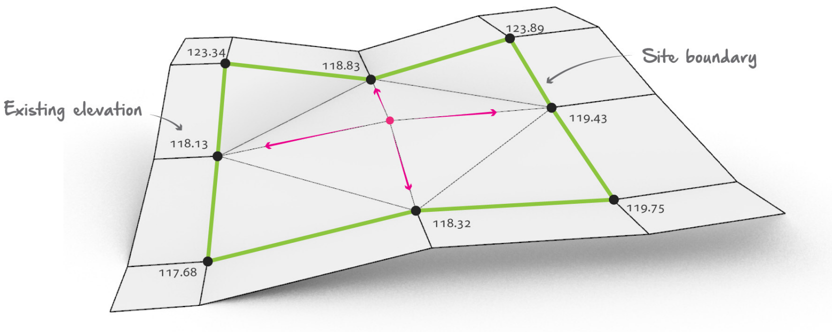

Fig. 3: A fully constrained parametric terrain model. In this simplified example, only one elevation point can be adjusted (marked in magenta).

2.3 The Evaluation Model

To understand which of the parametrically generated design option performs best, clear assessment criteria need to be specified. However, formulating the evaluation model in engineering, architectural, and landscape architectural projects, is often challenging. In our considerations, we distinguish between two differentiating features of landscape architectural design: its qualitative and quantitative performance. Site layout generally addresses higher-order aspects such as liveability, aesthetics, symbolic meaning, design intent, or interaction with the surroundings. Despite ongoing research in this field (SEDDON et al. 2020), these criteria are notoriously difficult to express as mathematical formulas which can be solved with absolute certainty. Therefore, architectural design optimization often uses numerical simulations to evaluate design options against arbitrary, quantitative performance criteria (FRICKER et al. 2019). Designers will not know whether the proposed scenario is the best possible, but they can examine and rank-order multiple options to ultimately choose the *best performing* one from the pool of analysed samples.

In recent years, this process, often referred to as *black-box* optimization, has become more popular in the field of architecture (FRICKER et al. 2020). It measures the performance of individual scenarios according to their *fitness* or *objective functions* and then ranks them accordingly. If multiple design objectives need to be considered, the fitness function can be defined as a weighted sum of their individual contributions. Finding the most optimal set of parameters constituting a design candidate is therefore equivalent to minimizing (or maximizing) the output of the governing objective function (WORTMANN & NANNICINI 2017).

The majority of CAD and GIS packages offer integrated solutions to perform quantitative analysis of topographical models. Given a 3D terrain representation, it is trivial to delineate catchment areas, estimate detention volumes or calculate cut & fill balance against the existing condition. For climate adaptation planning, we propose to combine these evaluation modes in one fitness function developed around design constraints described in previous chapters. To allow for direct comparison, all resulting values are normalized to one numerical domain, defined as the 0-1 range. Weights attached to each objective provide an additional mechanism to fine-tune their individual contribution. Table 1 summarizes the general formulas used for assessment of respective design objectives as well as the initial weights used for our case studies.

Table 1: Parameters used in the fitness function to evaluate performance of terrain models.

Variable	Unit	Formula	Weight
Slope range	%	0 = no. of el. | 1 = no. of el. * 5	1
Detention volume	m3	1 – (Provided / Required)	10
Cut & fill balance	m3	0 = 0 | 1 = max amount from pre-run analysis	5
Drainage coverage	m2	1 – (Provided / Required)	10

2.4 The Optimization Step

Once the fitness function has been defined, an efficient method for analyzing design options is needed. Due to the sheer number of elevation points involved in a typical terrain modelling project, such problems cannot be solved with brute-forcing methods in reasonable amounts of time (LUKE 2013). Therefore, we propose to resort to evolutionary algorithms (EA) – solvers proven in the field of architecture (NAGY et al. 2017), which seek near-optimal solutions. They employ principles of natural biological selection to create consecutive generations of design instances by slightly altering (mutating) their parameters (genes) at each iteration (MICHALEWICZ & FOGEL 2013). Values yielding best overall results have a higher chance of becoming parents for future generations of design options.

Multiple software implementations of EAs exist. For this study, we used *Galapagos* (GALAPAGOS 2019) – a free plugin for *Rhino*, which itself is a CAD package popular among landscape architects. Its visual programming interface allows for intuitive creation of optimization pipelines even for practitioners unfamiliar with the matter. In our case, slope values constitute the genome which describes a unique topographical model. Leveraging other analysis modules, Galapagos evaluates their fitness and alters the gene pool seeking for better performing combinations (Fig. 4). With each iteration, an initially random set of values, gradually converges towards the most optimal solution for the given site layout.

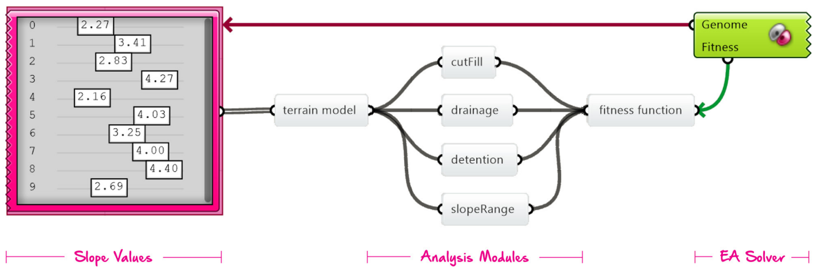

Fig. 4: A diagrammatic overview of the proposed optimization framework with Galapagos

2.5 Workflow Overview

A typical early residential development design process comprises of exploring several alternatives before settling on one scenario chosen for further development. In the proposed workflow high-level user input is augmented by low-level optimization strategies. Designers provide diagrammatic site layouts and define desired drainage patterns through establishing relationships between critical points. The actual elevation values are then calculated by EA with the goal of maximizing combined performance across four key analysis types (Fig 5). Depending on specific project requirements, their contribution to the governing fitness function can be adjusted with dedicated weights. To provide an example: in hilly terrain, maintaining low slope values might be of lesser priority than avoiding significant amount of earthworks. Conversely, introducing steep slopes to an otherwise flat landscape could be penalized more.

The proposed method does not result in one, most optimal design for a given site. Rather, it allows to analyze and benchmark several different site layouts and find their best performing topographical representations. This differentiates our approach from pure black-box parametric approaches, which – concentrating purely on the quantitative analysis – often lead to little reflected solutions. In the suggested workflow, the *soft* criteria are evaluated by humans, the *hard* ones – algorithmically. Our experience from landscape architectural practice shows that such approach typically enables informed conversations between all stakeholders involved in the planning process.

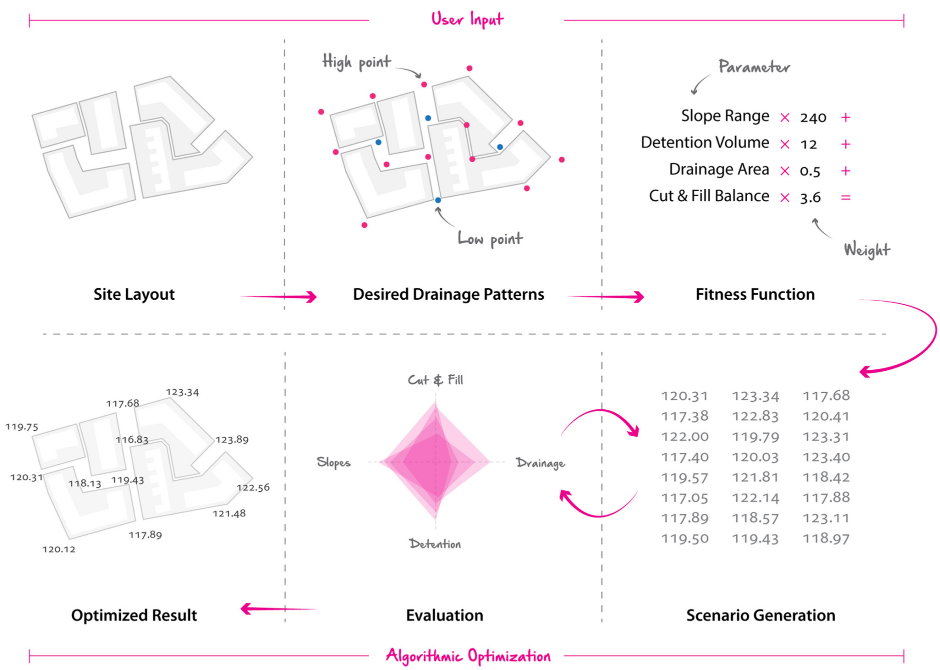

Fig. 5: Process diagram of the proposed 3D terrain modelling optimization method

3 Validation

3.1 Case Studies

The proposed approach was tested on 3 separate real-life projects coming from a professional landscape architectural practice. All situated in Germany, covering areas of 10 to 40 ha, and comprising of street layouts with mixed-use buildings and multifunctional green spaces distributed in various arrangements. These projects represent typical residential development challenges of European cities when it comes to climate adaptation planning and specifically stormwater management. They vary in size and complexity as well as the underlying topographical features of the existing ground. We compared the performance of terrain models created following the traditional approach in the studio, with the ones generated algorithmically using our proposed method.

Fig. 6: Site plan of the most complex case study – Castelnau 2. 86 elevation points were needed to meaningfully describe the desired drainage patterns for this site (© Ramboll Studio Dreiseitl)

Case study 1 – *Wohnen am Illerpark*

Covering approx. 10 ha of land, this site situated in Neu-Ulm was the smallest of our case studies. Existing terrain is relatively flat and currently used for agricultural purposes. The proposed stormwater management plan relied exclusively on Nature Based Solutions capable of detaining 1500 m3 of runoff during a 10-year rain event. Required volume was distributed across 4 centrally located infiltration swales. To convey stormwater to these elements, 48 elevation points were needed, which then served as a base for our parametric model.

Case study 2 – *Hellwinkel*

Situated in Wolfsburg, the site covers approx. 14 ha of relatively steep terrain sporting elevation differences of up to 6 meters. Existing land use was dominated by allotment gardens and concrete paths used for pedestrian and bicycle traffic. Because of high soil impermeability, the stormwater management concept couldn't include any infiltration elements. Instead, it relied on a combination of underground canals and multifunctional green spaces capable of temporarily storing up to 2500 m3 of runoff (Fig. 1). During a 30-year rain event, stormwater would run on the surface of the streets, which by design can accommodate up to 15 cm of water flow. A relatively simple layout of the proposed street network required defining only 24 elevation points to create the parametric terrain model.

Case study 3 – *Castelnau 2*

The site covers approx. 40 ha in Trier, making it the biggest and most complex of our case studies. Exhibiting elevation differences of up to 8 meters, it is situated on a former military proving ground with heavily contaminated soils. Steep natural gradient in conjunction with soil pollution ruled out the application of any infiltration measures. Therefore, also for this project's stormwater masterplan we resorted to a combination of underground canals and detention areas in designated green spaces. Required storage volume was calculated at 4500 m3 for a 10-year rain event. The relatively high complexity of the proposed site layout with winding streets and connecting paths necessitated 86 elevation points to meaningfully describe the proposed topography.

3.2 Results

For all cases, our approach resulted in higher fitness values than the manual strategy. Unsurprisingly, there were almost no differences in the categories assessing provided detention volume and drainage coverage. Since these are legally binding requirements, similar results are to be expected regardless of the chosen workflow. More significant differences were observed in the cut & fill balance. On average, the proposed method led to approx. 18% savings in earthworks and performed best on the most complex layout (Table 2). This can probably be attributed to the fact, that chances of human error in any type of problem-solving challenges are directly correlated to the increasing number of variables. Also, with increased number of elevation points, the algorithmic solver had more chances for micro-optimizations which add up to significant overall improvements.

Furthermore, we found that some constraints may conflict with each other given the initial site layout and the existing topography. This was especially pronounced in heavily sloping terrains when desired drainage patterns couldn't be achieved with slopes constrained to the 1-5% range. In these cases, either steeper slopes needed to be allowed for, or flow directions between selected points reversed. This feature alone proved to be a huge benefit of the proposed workflow. Some drainage patterns might be preferred for subjective reasons but – after further investigation – prove impossible to achieve within given constraints. The ability to identify these edge cases early in the design process and with relatively low effort allows practitioners to focus on refining alternative, more feasible solutions.

Table 2: Difference in cut & fill balance between the traditional and the proposed approach applied to our case studies (+ indicates that there is more cut than fill)

Case study	Traditional [m3]	Proposed [m3]	Difference [%]
Illerpark	+22 000	+20 000	9
Hellwinkel	+14 000	+12 000	14
Castelnau	+12 000	+8 000	33

4 Discussion

To verify the claim of our method being superior to manual terrain modelling, more rigorous real-world testing is necessary. In addition to analyzing a wider set of residential development projects, the methodology could be applied to other site typologies as well.

Currently, constraint weights have the most influence on resulting fitness of terrain models generated using our technique. Landscape architects must manually weigh these parameters in a trial-and-error way. Although such an interaction might reveal useful information about the challenges presented by a given site (SAUNDERS et al. 2001), it is a time-consuming effort, especially for practitioners unfamiliar with EA's operational principles. More systematic ways of determining the appropriate weighting criteria would therefore benefit the terrain optimization – and more importantly – the climate adaptation planning process. While it is not our goal to eliminate user interaction with the model, fitness functions could be calibrated in a semi-automated manner (EIBEN & SMIT 2011). Since this could free up time and human resources needed to investigate alternative site layouts, future work might focus on further developing this concept.

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