KPI-DRIVEN PARAMETRIC DESIGN OF URBAN SYSTEMS

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Abstract. We present a framework for data-driven algorithmic generation and post-evaluation of alternative urban developments. These urban developments are framed by a strategic placement of diverse urban typologies whose spatial configurations follow design recommendations outlined in existing building and zoning regulations. By using specific rule-based generative algorithms, different spatial arrangements of these urban typologies, forming building blocks, are derived and visualized, given the aforementioned spatial, legal, and functional regulations. Once the envisioned urban configurations are generated, these are evaluated based on a number of aspects pertaining to spatial, economic, and thermal (environmental) dimensions, which are understood as the key performance indicators (KPIs) selected for informed ranking and evaluation. To facilitate the analysis and data-driven ranking of derived numeric KPIs, we deployed a diverse set of analytical techniques (e.g., conditional selection, regression models) enriched with visual interactive mechanisms, otherwise known as the Visual Analytics (VA) approach. The proposed approach has been tested on a case study district in the city of Vienna, Austria, offering real-world design solutions and assessments.

Keywords. Urban design evaluation; parametric modelling; urban simulation; environmental performance; visual analytics.

1. Introduction

In recent years, the progressive application of computational design systems in urban design practices allowed for unprecedented and holistic explorations of a physical space. With conventional urban design and planning approaches being inherently inert and time-consuming, especially when it comes to consideration of numerous design alternatives and design optimizations, it is not surprising that these kinds of digital applications have brought about a new paradigm shift that led from analogue to a widespread digital thinking (Fink 2018). One of the most promising applications of such digital systems relate to parametric modelling, which, in principle, enables a multi-faceted assessment of form, design and, nowadays, even holistic environmental responses of considered planning

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strategies (Chowdhury and Schnabel, 2018; Vuckovic et al. 2017; Zhang and Liu, 2019). In general, the key advantages of parameter-driven approaches pertain to instantaneous visual feedback on the shape, dimensions, and spatial arrangement of model geometries once the desired parameters are modified. This allows for a timely consideration of multiple urban rules (e.g., spatial, structural regulations) and their interdependencies, which are then visualized and later can be evaluated based on an informed set of factors. This not only helps identify the potentially conflicting physical conditions and performance-related features, but it also supports urban designers when deciding upon the most optimal design solutions. Additionally, due to inherent flexibility and immediate visual response, these systems may foster real-time collaboration and participation of interested stakeholders in all stages of urban development (Steinø and Veirum, 2005). This is perceived as especially valuable considering that some more complex interventions in urban realm require substantial financial resources, along with time-intensive and well-coordinated planning and monitoring campaigns carried out by both urban planning and governing authorities. It can be thus said that parametric design procedures play a central part in sustainable collaborative urban transformation.

In this context, we aim to further exemplify the potential of such parametric approaches by applying a semi-automated workflow for data-driven algorithmic generation and analytical post-evaluation of alternative urban developments (Fink and König, 2019; Vuckovic et al., 2019). These urban developments are framed by a strategic placement of diverse urban typologies whose spatial configurations follow design recommendations outlined in existing building and zoning regulations, while offering some flexibility in open to closed ratio of resulting volumes. The proposed approach has been tested on selected building blocks in the ninth district in Vienna, Austria, offering real-world design solutions and assessments. Following, a performance assessment of resulting urban developments based on a defined set of KPIs is offered.

2. Methods

The novelty of our approach lies in the unique application of computational (parametric) modelling, environmental assessment approaches and interactive analytical techniques that are expected to unlock new perspectives in the collective field of urban science.

The envisioned parametric and environmental framework is set up within the 3D modelling software environment Rhinoceros 3D and its native plug-in Grasshopper (Rhino 3D, 2020). Whereby Rhinoceros 3D supports the generation and rendering of finitely-defined freeform 3D surfaces by utilizing NURBS (i.e., Non-Uniform Rational B-Splines), a mathematical representation of splines, Grasshopper (GH) complements and enhances Rhinoceros' capabilities by introducing a myriad of parametric functionalities. In our framework, the implementation workflow relies on a number of built-in and self-engineered modular components available in Grasshopper that allow for seamless data transfer between deployed generative components and simulation engines. Further complemented by advanced visual analytics techniques, the quality and performance of resulting parametrically derived spatial configurations is assessed given the selected KPIs. By carrying out the envisioned multidisciplinary steps of our framework, we likewise demonstrate the application potential of the framework itself.

2.1. RULE-BASED MODELLING OF URBAN SYSTEMS

As mentioned before, we considered six alternative urban developments (variant 1 to 6), each differing in the position and orientation of individual urban typologies. The spatial configurations of these individual urban typologies (i.e., fully-enclosed volumes with inner courtyards, semi-enclosed with partial openings, stand-alone volumes) follow design recommendations outlined in existing building and zoning regulations (LGBI, 2020; Stadt Wien, 2020). Thus, specific dimensional (e.g., vertical, horizontal restrictions) and spatial (e.g., geometry) constraints derived from the said regulations framed the resulting building assemblies (Figure 1). In the following step, specific rule-based generative algorithms are used to derive different spatial arrangements of these urban typologies, forming building blocks in ninth district in Vienna, given the afore-mentioned spatial, legal and functional regulations. These consider a set of explicit control inputs such as building class, maximal allowed building height, individual distances between the buildings, and relationship to the plot line.

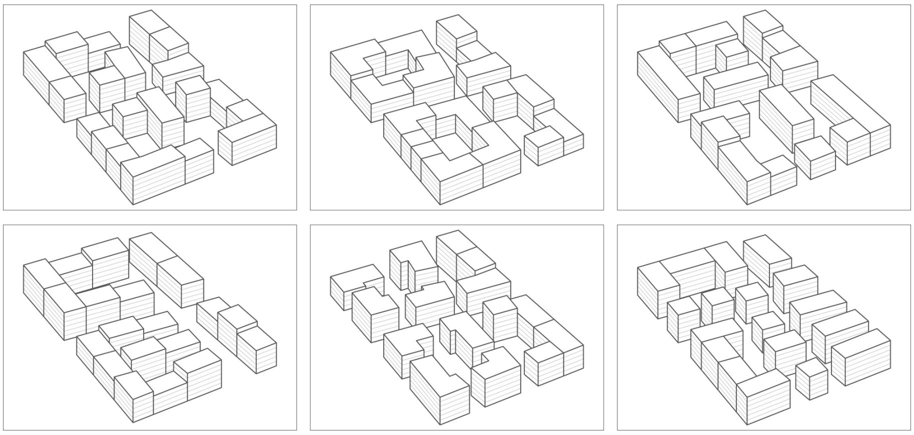

Figure 1. Figure 1. Six alternative urban developments composed of individual typologies.

2.2. SELECTED KPIS OF URBAN SYSTEMS

Once the envisioned urban configurations are generated, these are evaluated based on a number of aspects pertaining to spatial, economic, and thermal (environmental) dimensions, which are understood as the key performance indicators (KPIs) selected for informed ranking and evaluation. These namely entail the overall economic impact (construction and maintenance costs), built and open space ratio, green quality of urban space (trees), building energy requirements (heating and cooling demand), mean radiant temperature (MRT), universal thermal climate index (UTCI). Here, we focused on those urban aspects that are found to have an immediate effect on the quality of urban life (e.g., amount of green spaces, solar potential, heat stress, urban spatial structure, energy consumption).

Metrics pertaining to spatial dimensions are derived by conducting a spatial analysis of the resulting alternative 3D district geometry models, considering the respective transformations of physical environment, such as, the achieved buildable potential (built density, building height) and the resulting land cover configurations (ratio of unsealed to sealed cover - built-up area). These are namely derived using the readily available components in Grasshopper that allow for computation of areas [m^2] and volumes [m^3], whereby the respective values of each urban development iteration are then assessed in respect to the observed urban domain as a whole.

Metrics pertaining to economic impact relate to construction cost estimation arising from the newly formed urban structures, which was based on local construction cost index (BKI, 2020). As we aimed to reach a similar gross floor area (GFA) for each of the six alternatives, the economic impact is of a more qualitative character.

As an additional focal point of our investigations concerns thermal (environmental) response of considered solutions, we conducted a set of dynamic simulations of building energy and microclimatic conditions, providing thus a base for a comparative assessment and further design optimization. These are explained in more detail below.

2.3. ENVIRONMENTAL SIMULATIONS AND KPIS

Environmental and thermal assessments are carried out using the specific set of plug-ins from the family of Ladybug Tools (Ladybug Tools, 2020). Ladybug Tools (LBt) components allow for computation of complex interactions of built environment and climate resulting in detailed thermodynamic modelling on both urban and building scale (Vuckovic et al., 2019). To carry out such computations, a representative climate information via hourly-based weather file is provided, whereby we based our simulations on typical reference year composed for Vienna (EnergyPlus Weather, 2020). Subsequently, the building geometry is converted into thermal zone volumes (HB zones) with all thermal property information required to initiate an energy performance simulation (e.g., construction materials, surface boundary conditions, heating/cooling systems, occupancy schedules). Same transformation is done for ground surfaces, whereby all distinct soil types are identified and appropriate thermal properties assigned (e.g., asphalt roads, grass surfaces). With the model properly set up, annual energy simulation is carried out using the LBt-linked connection to EnergyPlus software (EnergyPlus, 2020). LBt-native Microclimate Map Analysis component is deployed towards the computation of desired thermal comfort indices (MRT, UTCI). These are then expressed through an area average and used as the KPIs for further evaluation.

2.4. VISUAL ANALYTICS FOR RANKING OF URBAN SYSTEMS

To facilitate the analytical analysis of derived numeric KPIs, to achieve data-driven ranking of generated design alternatives, we deployed a diverse set of analytical techniques (e.g., conditional selection, regression models) enriched with visual interactive mechanisms, otherwise known as the Visual Analytics (VA) approach. For this purpose, we used high-performance analytical VRVis Cockpits that allow for synthetizing the computed numerical and categorical data into cohesive and well-founded insights (Vuckovic and Schmidt, 2020). We pursued a 3-pillar approach, whereby all KPIs are fused into 3 distinct categories: spatial, economic, climate. We aimed for high GFA and low amount of sealed cover in spatial, low construction and maintenance costs in economic, and low MRT and UTCI values in climate category.

3. Results and Discussions

The considered urban design variants show a range of spatial variations, both in individual placement of volumes and resulting metrics. These are summarized in Table 1. It can be seen that those variants having the highest buildings (i.e., variants 5 and 6), at the same time take the least of the ground surface. This may be understood as potentially beneficial for allowing a desirable ratio of supplementary green infrastructure (trees and parks), thus increasing the overall quality of urban space. In terms of the construction costs, variants 1, 3, 4 and 6 were found to be the most expensive to construct, however these also allowed for the highest GFA to be reached. This insinuates potential confronting decisions during the evaluation stage, and these will be reflected upon at later discussion.

Table 1. An overview of selected computed KPIs.

VAR	GFA [m2]	Built-Up Area [m2]	No.of Trees	Building Height [m]	Construction Costs [EUR]	Total Load [kWh/m2]	Avg. UTCI [°C]
01	28776	5528.41	15	15.6	31942000	33.73	36.75
02	27731	6207.49	14	13.4	30782000	34.40	36.85
03	28701	5538.89	14	15.6	31859000	32.90	36.84
04	28733	5630.99	17	15.3	31895000	34.55	36.80
05	27788	5166.58	16	16.2	30845000	32.77	36.70
06	28772	4932.98	16	17.33	31938000	33.02	36.58

Looking at the spatial distribution of simulated thermal indices (we exemplify here the case of UTCI), a varying potential for solar shading by physical constructions may be observed across all six variants. It can be noted that the higher the distance between buildings, the higher potential for hot spots emerging. This is clearly visible in southern domain in variant 3 and southern and northern domains in variant 4, where UTCI tends to exceed 41°C. This may be, in part, mitigated by denser arrangement of trees, whereby the beneficial effect of such measures may be observed in the same southern domain in variants 1, 2 and 3. The potential reduction in UTCI equals 4.5°C. It can be further stated that having enclosed urban forms forming inner courtyards, as visible in variant 2, may result in favourable thermal conditions within. This may lower the cooling energy demand for living units facing courtyards, due to the overall reduction in direct solar gains. However, due to the lower sky view factor (SVF), this may also negatively affect the night-time cooling potential. This may be especially critical in smaller courtyards with a higher height-to-width ratio (i.e., narrower courtyards with higher buildings). Similarly, semi-enclosed tight tunnel-like formations, as seen in variant 4, may be beneficial during the day, due to reduced solar gain, but equally unfavourable during the night, due to the potential accumulation of heat caused by impeded air flow and SVF. On the contrary, semi-enclosed irregular formations, as seen in variants 1 and 3, allow for adequate spacing between buildings and unrestricted air flow, with likely favourable thermal effects. Finally, when considering fully-open stand-alone formations, as seen in variant 6, and especially when complimented with a balanced positioning of trees, we may achieve the optimal percentage of beneficial thermal conditions.

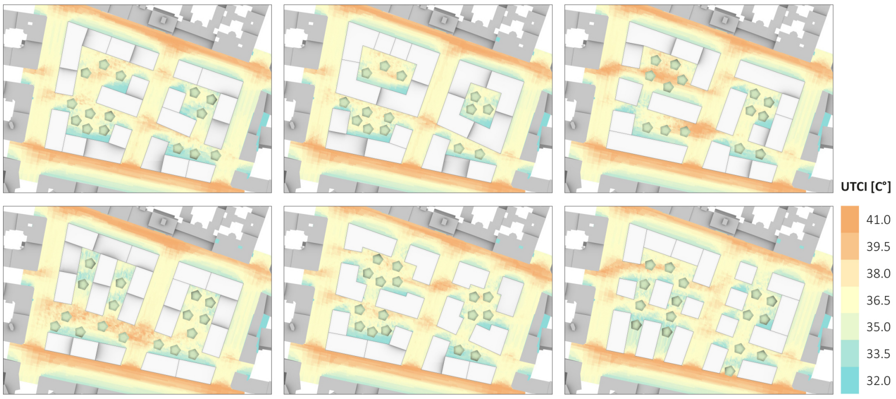

Figure 2. UTCI simulation results calculated for the six typologies.

Looking at the building level, the floor-by-floor distribution of total annual thermal loads (i.e., combined heating and cooling load) appears to vary to a slight degree. As expected, the fully exposed higher floors endure the highest absorption of incoming solar radiation, as seen in all variants. This might be partly mitigated by consideration of unequal building heights, which may promote solar shading caused by surrounding higher volumes. In agreement with our previous discussion, the spatial arrangement of individual urban typologies may likewise affect the resulting thermal loads. This means that the higher the distance between the buildings (variants 3 and 4), the higher the exposure of building facades to solar radiation, resulting in greater thermal loads. The same may be said for the stand-alone building volumes, as they have less volume to be heated up and higher solar exposure on all facades, resulting in faster warming rate. Again, this may be mitigated by strategically placing the surrounding trees, where potential improvements to this end may be identified in variant 6. Looking at the heating and cooling loads independently, our results suggest almost no difference to annual cooling loads, but some in annual heating loads. Variants 5 and 6 seem to perform the best, whereby variant 4 reveals the highest heating loads.

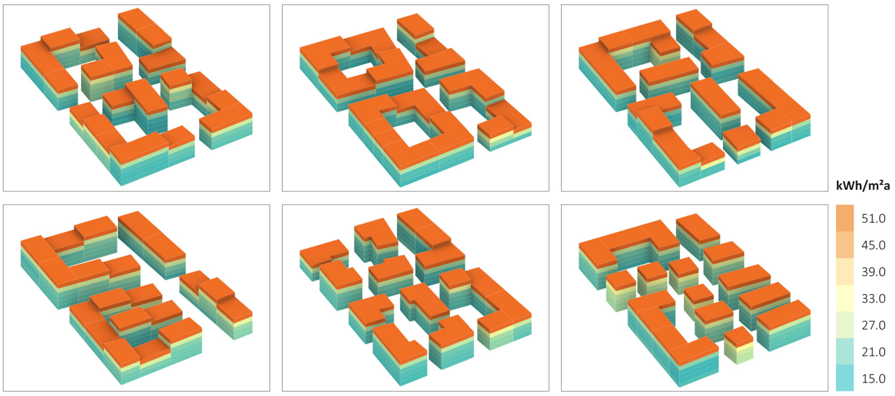

Figure 3. Total thermal load (representing heating and cooling demand) per floor in kWh/m²a for residential use.

We proceeded with the analytical evaluation of the derived KPIs. Figure 4 exemplifies the interlinked system and instantaneous visual feedback (e.g., heatmaps, parallel coordinates) of deployed VA system by considering all KPIs and 6 spatial variants (i.e., design alternative). Here, the green-red heatmap (upper section of Figure 4) denotes the degree to which certain variant (1-6) meets the set KPI requirements - red color indicating that such requirements are exceeded, and green indicating that these are met. Parallel variants comparison (lower section of Figure 4) provides a parallel analysis of all the variants while highlighting those where the set requirements are met. More specifically, by applying user-defined conditional selections (e.g., high GFA, low UTCI) to each of the investigated pillars (spatial, economic, climate), we identified the most optimal spatial variant given these specific framing conditions. Namely, spatial and climate requirements revealed variant 6 as the most optimal, whereby economic requirements identified variant 5 (Figure 5). More specifically, Figure 5 offers a comparative visual analysis of those variants that met the most of the set KPIs, further observed from the perspective of each of the considered pillars (spatial, economic, climate). In the following step, we conducted a deeper analysis of the two, while considering all KPIs simultaneously (Figure 6). Figure 6 thus provides a visual analysis of two isolated variants and the ways they respond to each of the KPI. This revealed a clear inversed trend and potential inter-correlations between multiple KPIs considered, further confirmed by conducting a correlational analysis, where we noted a positive correlation between, for example, GFA and construction costs. Such a comparative analysis indicated the height of decision complexity and a general inability to meet all set requirements.

Figure 4. Interlinked high-performance analytical VRVis Cockpits.

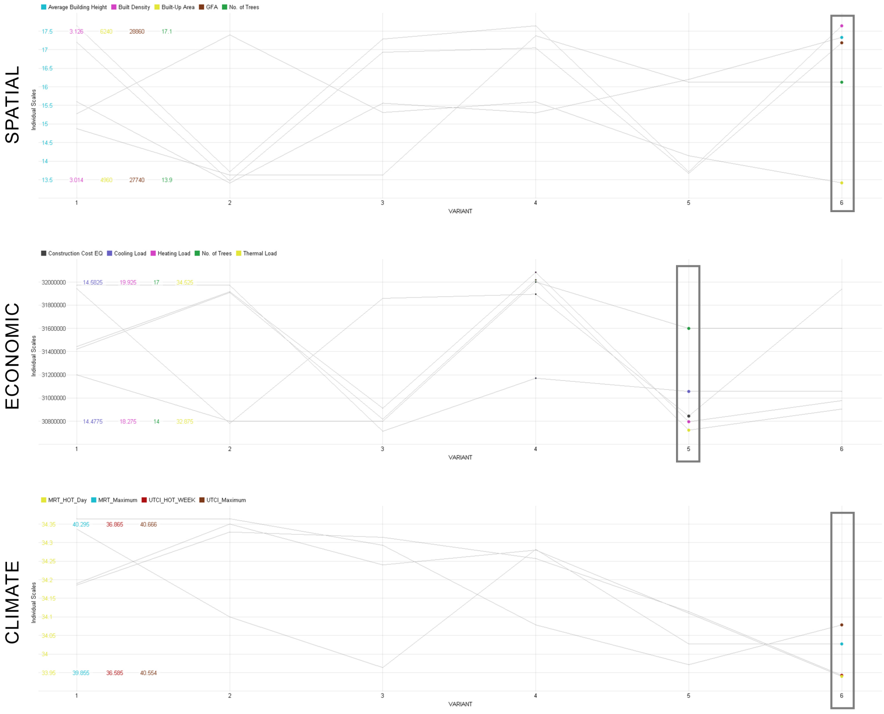

Figure 5. Most optimal variants as a result of the 3-pillar driven conditional selection.

Figure 6. Inversed trends in variants 5 and 6, with target KPI values marked in yellow.

4. Conclusions

There is an evident application potential of parametric design approaches for informed KPI-driven assessment of urban systems. Not only that, more urban alternatives may be simultaneously generated at very low computational costs, but these may be easily formulated within the existing building and zoning boundaries. Additionally, the key spatial metrics may be effortlessly derived from the resulting 3-dimensional representations of envisioned design alternatives. The added value to such a parametric approach is its enhanced environmental functionality that allows for the multi-dimensional assessment of climate and energy nexus. Complemented with exploratory data analysis workflows encapsulated within the Visual Analytics system, the entire framework becomes a powerful decision-support tool, invaluable to urban planners, architects, municipalities and other relevant stakeholders. In conclusion, this unifying framework allowed us to readily identify the most optimal solutions given the set of evaluative KPIs, however, it also uncovered the complexity behind decision-making and stressed the need for a certain degree of flexibility when trying to meet defined targets. Potential limitations to our approach relate to the confined consideration of only 3 pillars (spatial, economic, climate), where other aspects, such as accessibility, air quality, wind comfort, noise pollution, should certainly be integral to such appraisals. We are thus currently working on enhancing our framework to include a more comprehensive set of aspects.

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