VitalVizor: A Visual Analytics System for Studying Urban Vitality

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Creating lively places with high urban vitality is an ultimate goal for urban planning and design. The VitalVizor visual analytics system employs well-established visualization and interaction techniques to facilitate user exploration of spatial physical entities and non-spatial urban design metrics when studying urban vitality.

Urban planning and design aim to improve social and environmental wellbeing in cities. As cities become increasingly complex and dynamic, urban design methods are shifting from traditional subjective and qualitative approaches to quantitative assessments of urban data. Urban vitality, as an indicator of lively urban experiences, has become increasingly crucial for contemporary evidence-based urban design.[1] The term reflects quality of built environments, which consist of physical entities, including streets, blocks, and buildings. Consequently, urban vitality can be studied by analyzing essential urban design metrics tied with these physical entities, such as street accessibility, building density and typology, and function mixture.

A series of GIS tools has been developed for studying urban vitality. For instance, sDNA (www.cardiff.ac.uk/sdna/), a tool developed on the basis of space syntax theory, has been widely used to measure street accessibility. However, these tools usually focus on only one or a few individual metrics. To systematically study urban vitality, planners and designers are compelled to generate intermediary measurements with these tools separately, and then integrate the measurements together. The process is not only tedious and time-consuming, but it can also be problematic, as no direct visual feedback is provided for the experts to evaluate.

To overcome these deficiencies, an interactive visual analytics tool that facilitates the exploration process is preferred by domain experts. Nevertheless, developing such a tool is nontrivial, as the visualization needs to present both physical entities (spatial information) and urban design metrics (non-spatial information). By nature, the physical entities exhibit a multiscale property, and the various metrics are multidimensional. More importantly, a preliminary study[2] has shown that the urban design metrics can be organized in a hierarchy: The topmost level gives an overview of urban vitality, which is determined by categories of implicit metrics in the middle level, and the lowest level reveals explicit metrics directly measured from the physical entities (such as local

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accessibility derived from a street network). The experts would like the visual analytics to support both overview and details-on-demand exploration of urban vitality; the tool should support exploration of multiscale physical entities, as well as multidimensional and hierarchical urban design metrics.

In this work, we introduce VitalVizor, an interactive visual analytics system that allows planners and designers to effectively study urban vitality for evidence-based urban design. VitalVizor mainly consists of two visualization modules:

- Map View, to show geographical information about the physical entities (such as streets, blocks, and buildings) in a study area.
- Metric View, to present the urban design metrics. This view is a well-integrated visual representation that combines a tree diagram—which presents the hierarchical structure of all metrics—with parallel coordinate plots (PCPs)—which show correlations among the lowest-level explicit metrics. Various user interactions, including filter and focus, are implemented to support exploration of details.

The major contributions of this work include:

- VitalVizor, an interactive visual analytics system that helps planners and designers systematically study urban vitality. To the best of our knowledge, our system supplements the gap between domain experts' requirements and existing tools. This is a well-integrated visual representation that combines PCPs with a tree diagram to fulfill analysis requirements.
- Application of VitalVizor using a real-world dataset along with consulting studies with domain experts. Our goal was to identify blocks with imbalanced metrics that could be improved feasibly.

RELATED WORK

Today, vast amounts of urban data are being collected due to rapid advancements in sensing technologies. Big urban data has shifted urban design from long-term strategic planning to short-term thinking about city functionality and management. This fosters an emerging research topic: evidence-based urban design. Visual analytics has proven useful in many applications, such as transportation[3] and urban environments.[4]

Most of these visual analytics focus on revealing spatial and temporal characteristics of dynamic urban data, as the data are invariably tagged to space and time. In contrast, less effort has been put into visualizing and analyzing static physical entities of built environments in a city, including streets and buildings, where an urban-planning project usually takes place. Karduni et al.[5] conducted a survey on identifying important elements for different occupations within a city context, which reveals that urban planning requires information about land use, streets, density, and so on. These metrics are closely tied to the physical entities.

Urban researchers usually adopt GIS tools for studying urban design metrics. Jiang et al.[6] integrated space syntax into a GIS framework to help planners analyze spatial configurations of street networks. This analysis capacity can be augmented with a feasible protocol that can automatically transfer polyline data from worldwide OpenStreetMaps into a GIS-workable format.[7,8] However, Ratti[9] later figured out that space syntax is solely based on topological representation of cities—it ignores other metrics such as building heights and land use, which are also essential metrics for accessing design quality of a city. Hence, many other methods, such as mixed-use index (MXI)[10] and spacematrix,[11] were developed to complement space syntax. Recently, Ye and van Nes[2] measured these metrics with separate tools and combined them into a single quantitative grid system in ArcGIS. However, many deficiencies, such as no direct visual feedback and poor support of 3D exploration, are realized.

Closely related to our work, several visual analytics platforms that focus on both spatial physical entities and non-spatial analysis data have emerged. Among them, Chang et al. developed Urban

Vis that allows users to explore the relationship between spatial 3D models and multi-dimensional census information.[12] Waser and his colleagues developed Visdom, which combines simulation, analysis, and visualization to support decision-making in city planning and management, including flood management and risk evaluation.[13] Ferreira *et al.* designed Urbane,[14] which integrates multiple data layers and impact analysis to study effects of buildings regarding landmark visibility and sky exposure. Their work was advanced by Vis-A-Ware,[15] which provides an additional ranking view that efficiently compares multiple building candidates. In comparison with typical 2D visual analytics of big urban data, these visualizations exhibit a common feature of supporting 3D views of building models in a city.

These visual analytics employ a common visualization layout that combines a map view, which supports multi-resolution exploration of spatial information, and an analytic view, which presents abstract data tied to the physical space. Typically, a PCP is integrated in the analytic view if multidimensional analyses are required. However, the systems neglect the hierarchical structure of urban design metrics required in urban-vitality studies, thus failing to support details-on-demand exploration from the metrics perspective. In contrast, VitalVizor seamlessly combines a PCP with a tree diagram to reveal both the multidimensional and hierarchical information about the metrics. Spatial-filter and metrics-focus interactions are further integrated in the system to support details-on-demand exploration from both spatial and metrics perspectives.

BACKGROUND AND DOMAIN PROBLEM

In this section, we first introduce relevant terminologies, followed by characterization and abstraction of the data. Finally, we break down domain problems into analytical tasks.

Urban Vitality and Urban Design Metrics

In initial stages of the study, we had several discussion sessions in which a collaborating architect (CA) clarified the concept of urban vitality to us. As pointed out by the CA, urban planning and design is a practice of arranging physical entities of built environments to improve the living experience (in other words, urban vitality[1]) for citizens. As illustrated in Figure 1, physical entities of a built environment mainly consist of street networks, blocks, and buildings.
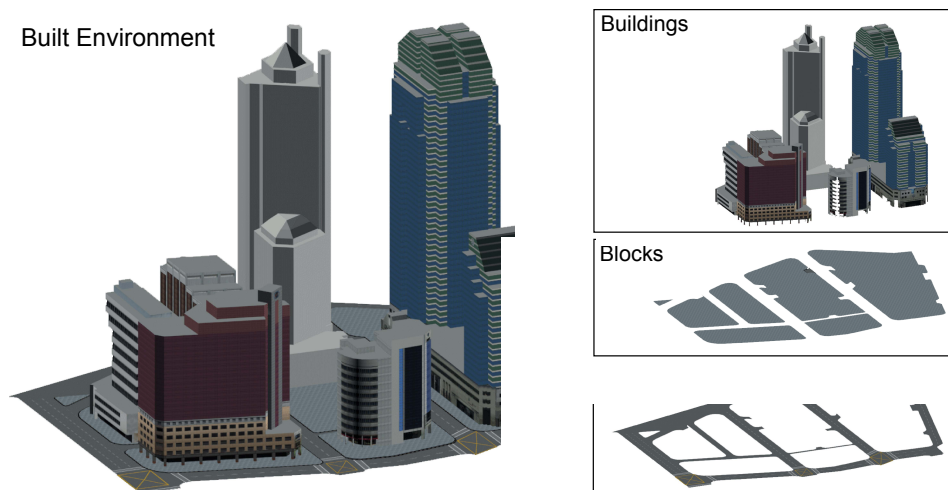

Figure 1. A built environment in a city is made up of physical entities mainly consisting of street networks, blocks, and buildings.

Nevertheless, urban vitality is intangible and subjective, hindering its applications in real design projects. To overcome this issue, many urban design metrics that quantitatively characterize the physical entities, including street accessibility, building intensity, and mixed usage, have been proposed for studying urban vitality.

Recently, an empirical study[2] summarized all urban design metrics related to urban vitality into the following three categories:

- *Street accessibility.* This measures spatial integration of street networks and has been applied to explain movement flows, economic activities, and street lives. It can be measured with various network configurations, including distances, turns, and angle changes. In addition, the metric can be further categorized as local and global accessibility, depending on a spatial bandwidth filtering the area surrounding a street network to be measured.
- *Density and typology.* This reflects intensity and compactness of buildings, as well as non-built space in a block. The metric depends on two measurements: floor space index (FSI), which reflects building density (high-, mid-, and low-rise), and ground space index (GSI), which reflects building typology (point-, strip-, and block-type). Based on these two metrics, density and typology can be expressed as one of nine groups (for example, high-rise point-type, mid-rise strip-type, and low-rise block-type[11]).
- *Function mixture.* This quantifies degrees of land-use mixture in a block. Here, land-use types are summarized into three categories: "Housing" includes apartments, condos, and townhouses; "working" includes offices, factories, and laboratories; and "amenity" includes commercial, educational, and leisure. The three metrics then determine a block's MXI as mono-functional, bi-functional, mixed, or highly mixed.[10]

The three categories also behave as metrics and determine urban vitality. Specifically, street accessibility contributes to urban vitality, as it determines through-movement potentials on streets. High accessibility encourages people to go through streets, which would create a lively atmosphere and potential chances for social activities. FSI normally represents high population density and thus tends to positively affect urban vitality. GSI affects the total number of public frontages proportional to interactions between buildings and streets, which could enhance urban vitality, as well.[1] In addition, function mixture reflects how people use an area during the day and night. Function mixture also helps achieve diversity in people and functions, which are foundations for cultivating urban vitality.[10]

Data Characterization and Abstraction

Physical entities

The street networks, blocks, and buildings can all be categorized as spatial data, which can be further categorized as 2D lines, 2D polygons, and 3D data, respectively. Like all spatial data, physical entities can be organized in multiple scales, from neighborhood to district to city scale.

Street accessibility is measured solely on street networks, while density and typology and function mixture are determined by blocks and buildings. Hence, first, we need to determine a common physical entity that can mingle all metrics. In this work, block is chosen with two considerations: First, blocks naturally act as an intermediary between street networks and buildings, as shown in Figure 1; second, from the perspective of visualization, blocks are more noticeable than street networks, especially when overviewing the metrics at a large scale, such as city scale.

Urban design metrics

There is a hierarchical relationship among non-spatial metrics; urban vitality is implied by three categories of metrics, while each category itself is a metric and is further implied by two or more metrics. In this work, we classify all metrics as one of the following:

- *Explicit.* These metrics can be directly computed from physical entities. Examples include local and global accessibility, FSI and GSI, housing, working, and amenity.
- *Implicit.* These metrics are determined by various explicit metrics. Examples include urban vitality, street accessibility, density and typology, and function mixture.

The explicit metrics belong to quantitative data types, while implicit metrics are either ordinal (such as function mixture) or categorical (such as density and typology). VitalVizor treats all metrics as ordinal data types and applies consistent visual and color encodings. This is accomplished by dividing quantitative data into ordered bins and ordering categorical data.

Analytical Tasks

The overall goal of this work is to design a visual analytics system that helps urban planners and designers study urban vitality. Because urban vitality is determined by various urban design metrics deduced from physical entities of a built environment, we can decompose the domain problem into the following analytical tasks:

- *Task 1: Ability to explore physical entities*. The system should allow users to explore different layers of physical entities, including 2D street networks and blocks and 3D buildings (T.1.1). Efficient interactions are required to assist users in exploring details of urban vitality at different scales (T.1.2).
- *Task 2: Ability to analyze urban design metrics*. The system should present histograms of each metric (T.2.1) and reveal the hierarchical relationships between all metrics (T.2.2). Specifically, the CA would like to explore correlations of explicit metrics (T.2.3).

Both pieces of information should be coordinated; an operation on physical entities should be reflected in urban design metrics, and *vice versa*.

VITALVIZOR FRAMEWORK

As shown in Figure 2, the framework of VitalVizor consists of three components.

Data Management

Our work studies three groups of physical entities of a built environment (street networks, blocks, and buildings), which can be classified as 2D-line, 2D-polygon, and 3D-data layers, respectively. Besides loading individual data layers, we also generate a mapping index that correlates street networks with blocks, as well as another one that correlates buildings with blocks in this stage.

Metrics Analysis

In this stage, we first compute explicit metrics from loaded physical entities. All metrics are assigned to blocks by mapping corresponding street networks and buildings to blocks. On the basis of these metrics, we deduce implicit metrics at the next level (street accessibility, density and typology, and function mixture), and finally deduce urban vitality. A hierarchical structure of all metrics is reserved.

Interactive Visual Exploration

The loaded physical entities and computed metrics are finally visualized in this stage. The interface mainly consists of two visualization components: Map View for Task 1 and Metric View for Task 2. The Map and Metric Views are coordinated, and they complement each other in supporting the study of urban vitality. Map View supports 2D/3D switching for exploring different data layers, and it allows users to specify a region of interest with various filtering tools. Metric View integrates a tree diagram to reveal hierarchical relationships among all metrics, as well as a PCP to present correlations of explicit metrics. The view also supports various interactions, such as focusing on subsets of metrics.
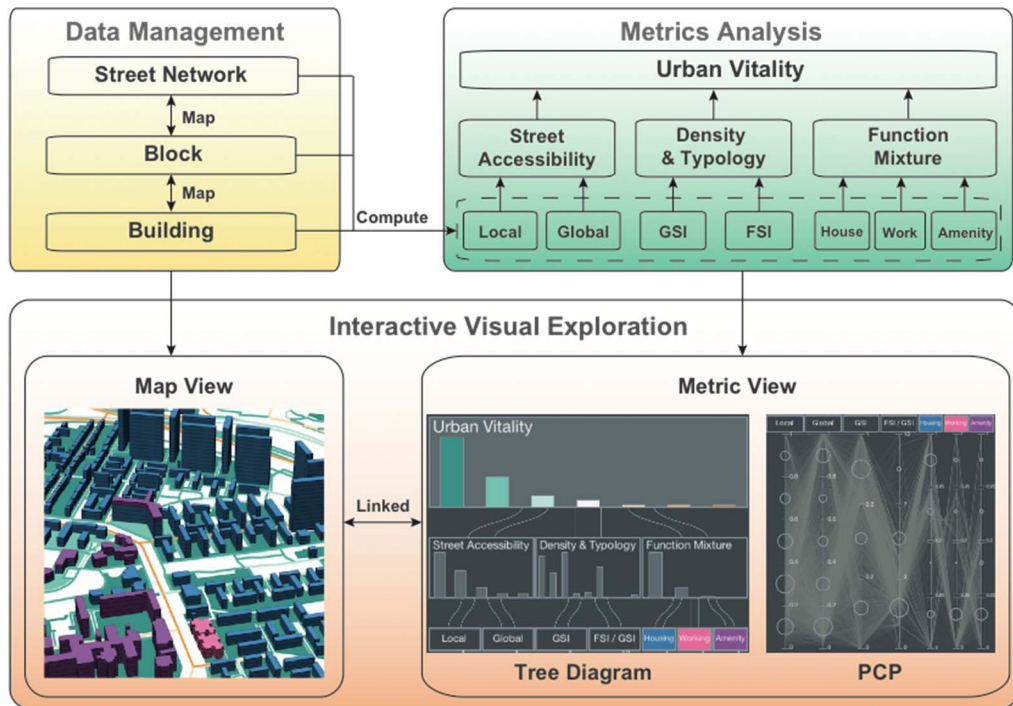
Figure 2. Overview of VitalVizor workflow, which consists of three components: data management, metrics analysis, and interactive visual exploration.

PHYSICAL ENTITIES AND URBAN DESIGN METRICS

This section describes physical entities and methods for quantifying urban design metrics.

Physical Entities

Street network

The network consists of 2D lines read from a shape file. The lines are modeled as an undirected graph $G = (N, E)$ where N is the set of nodes representing intersections in the street network, and E is the set of edges connecting neighboring nodes and representing streets in the street network. To facilitate the computation of accessibility, we simplify G into a reduced graph $\breve{G}$ by merging degree-two nodes such that $\breve{G} = (\breve{N}, \breve{E})$ consists of only ends and junctions. Here, $\breve{N} \subseteq N$, and a reduced edge $\breve{e} \in \breve{E}$ consists of a sequence of edges $\{e_1, ..., e_n\}$ where $1 \leq n \leq |E|$ and $e_n \in E$. The lengths of $\{e_1, ..., e_n\}$ are aggregated and assigned to $\breve{e}$. Here, $\breve{G}$ is only used for reducing the amounts of searching edges when computing accessibility, while the original input graph is used for visualization. Similar network simplification is commonly employed when analyzing street networks, such as OSMnx.[8]

Block

The blocks are read as 2D polygons from an input shape file. Each polygon consists of one or more rings, where each ring is a sequence of vertexes forming a closed loop. If vertexes are clockwise, a ring is an outer circle; otherwise, the ring is an interior hole. The area of a block can be calculated as aggregated area of outer rings deducting aggregated area of interior holes.

Building

A building is made up of a footprint and floor numbers of housing, working, and amenity functions. Similar to blocks, building footprints are represented as 2D polygons in a shape file. Additionally, each polygon includes attributes of floor numbers of the three functions. For visualization, we assume each floor is 3.5 m in height.

To map blocks with street networks, we find n nearest edges surrounding a block, where the distance is defined by calculating proximity of a line to a polygon. n is specified as 10 by the CA. To map blocks with buildings, we check whether the outer rings of a block contain the polygon of a building footprint.

Urban Design Metrics

After loading physical entities and generating mappings, we compute the metrics as follows.

Street accessibility

We adopt angular betweenness, which is a widely accepted measurement by space syntax experts to measure street accessibility. Here, the reduced graph $\check{G}$ is first converted to a dual graph where each street is represented as a node and each intersection is considered an edge. Then, an angular cost is measured for each intersection proportional to the angle of incidence of two streets at the intersection, which is defined as 0 for straight streets, 1 for right angle, and 2 for 180-degree angular turn. Last, the angular costs are applied as a weighting function to the betweenness measurement that is defined as the fraction of all shortest paths that pass through a street. More detailed descriptions can be found in the Al-Sayed *et al*. study.[16]

Specifically, local accessibility is measured by first filtering a subset of edges $\check{E}_x \subseteq \check{E}$, where Euclidean distances of edges in $\check{E}_x$ to $\check{e}_x$ are under a threshold *thre*. Then, local accessibility can be computed in the same way as described above. In this work, we set *thre* to 800 m, which is approximately 10-minute walking distance. An empirical study shows that this distance works well for mapping pedestrian accessibility.[17] Both global and local accessibility are normalized to [0, 1] and divided into five equal-size ordered bins.

Density and typology

Given a block bk and a set of buildings $\{bd_1, bd_2, ..., bd_m\}$ located in bk, GSI for bk can be measured as the sum of all building footprint areas divided by the area of bk, while FSI for bk can be measured as the sum of all building floor areas divided by the area of bk. A third metric $L_{bk} =$ FSI$_{bk}$ / GSI$_{bk}$, which represents mean floor number of buildings $\{bd_1, bd_2, ..., bd_m\}$, can be deduced. L can better indicate building density than FSI.

Based on a study of large numbers of blocks and buildings in many European cities,[11] we divide GSI into three ordered bins of [0, 0.2), [0.2, 0.3), and [0.3, 1], corresponding to point, stripe, and block type of typology, respectively. We divide L into three ordered bins of [0, 3), [3, 7), [7, $+\infty$], corresponding to low-, mid-, and high-rise types of density, respectively.

Considering both GSI and L, nine categories of density and typology are derived.

Function mixture

For each building bd in a block bk, we know the number of floors used for housing, working, and amenity functionalities. We can compute the ratio R of each individual functionality as the sum of all building floor areas used for the functionality divided by the sum of all building floor areas. Each R is in the range [0, 1], which is divided into four ordered bins of [0, 5%), [5%, 20%), [20%, 95%), and [95%, 100%], according to the van den Hoek study.[10] By combining the three individual ratios, we can get an MXI in one of four types: mono-functional, bi-functional, mixed, and highly mixed. A block is mono-functional when one function ratio is in the bin [95%, 100%]. If one function ratio is in [0, 5%), while neither of the other two is in [95%, 100%], the

block is bi-functional. If all three function ratios are in the bin [20%, 95%], the block is highly mixed. All other blocks are mixed.

These implicit metrics further classify urban vitality into seven bins.

VITALVIZOR INTERFACE

In this section, we first introduce rationales behind our visual designs, then elaborate on the visual encodings and user interactions.

Design Rationales

After identifying the analytical tasks and computing urban design metrics, it remains a challenging task to design an effective visual interface. We consider the following rationales in our design:

- *Coordinated multiple views (CMVs)*. The Map View and Metric View, as illustrated in Figure 3, present spatial physical entities and non-spatial metrics, respectively.
- *Overview and details*. To facilitate user exploration, we follow the information-seeking mantra: overview first, zoom and filter, and then details on demand.[18] VitalVizor first provides an overview of urban vitality over a whole city, then allows users to explore details of a specific area or some metrics on demands. Efficient filtering and focusing interactions should be provided to enable details-on-demand exploration.
- *Visual consistency*. We adopt a common diverging color scheme from ColorBrewer (www.colorbrewer2.org) to indicate metric bins in both views and across multi-scales to accomplish visual consistency, as shown in the bottom-right corner of Figure 3(a). We also considered some sequential color schemes, but the CA thought the differences were not intuitive, especially for metrics with many ordered bins (for example, density and typology has nine). We reserve separate colors for different function types (for example, light blue for housing, brown for working, and purple for amenity, as shown in Figure 4).
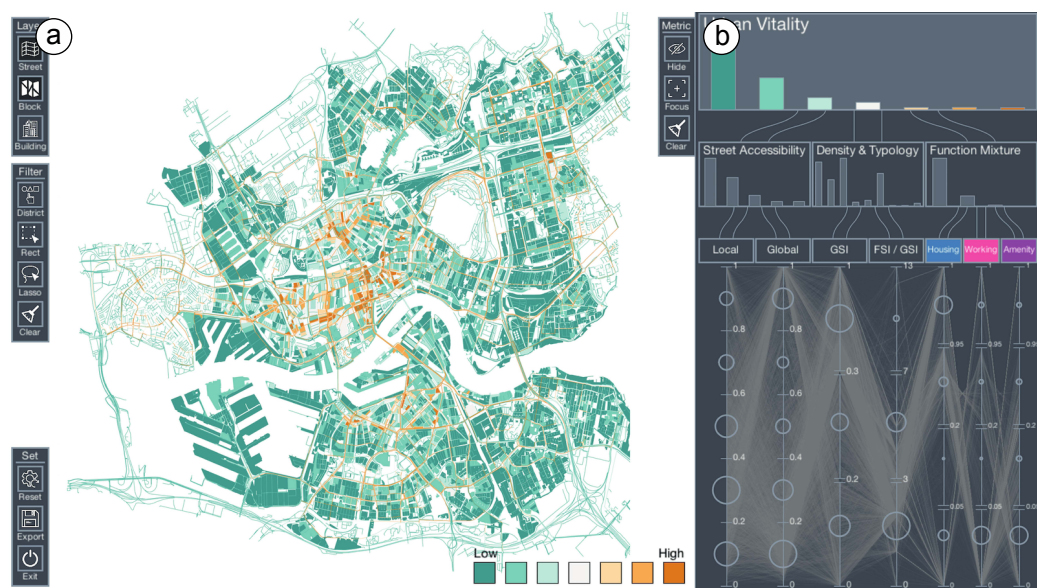

Figure 3. Overview of the VitalVizor interface, which consists of two coordinated views: (a) Map View, which presents physical entities, and (b) Metric View, which reveals urban design metrics. Various panels and buttons are overlaid to facilitate user exploration.
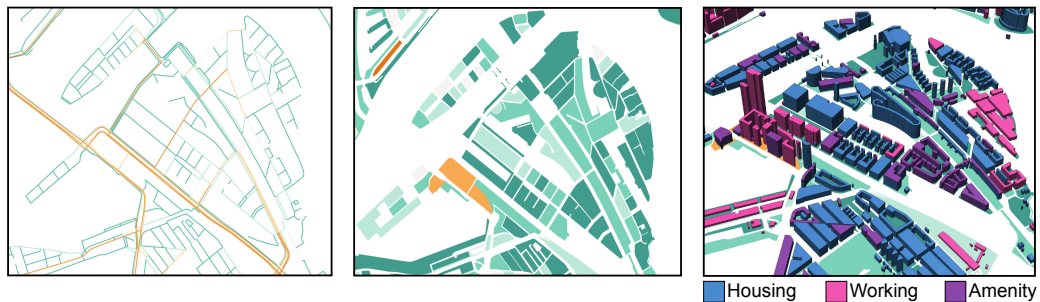
Figure 4. Map View supports rendering of street networks (left), blocks (middle), and buildings (right).

Map View

This view is designed to support exploration of physical entities (Task 1). It supports rendering components of 2D lines for street network (Figure 4 (left)), 2D polygons for blocks (Figure 4 (middle)), and 3D for buildings (Figure 4 (right)) (T.1.1).

Street networks and blocks are colored according to their corresponding metric values, while buildings are rendered as compositions of floors colored in accordance to function types. Basic map navigations, such as panning and rotating, are supported through mouse interactions. A set of overlaid panels and buttons are implemented. For instance, users can show or hide any data layer by enabling or disabling the corresponding button in the Layer panel.

Figure 3(a) shows a map overview of street networks and blocks. The blocks are colored according to their urban-vitality values, while street networks are colored according to street-accessibility values. Notice that street networks are always colored according to street accessibility, unless the exploration metric is specified as local or global accessibility in Metric View. The view shows that blocks with high vitality are concentrated in the center, while the outbound blocks have lower vitality.

Metric View

This view is designed for analyzing urban design metrics (Task 2). The view integrates a tree diagram to reveal hierarchical relationships among all metrics (T.2.2) and a PCP to present correlations of explicit metrics (T.2.3). The tree diagram is arranged in a vertical layout, while the PCP is horizontal, such that they form a compact design.

In the tree diagram, each metric is represented by a rectangle with a corresponding label, and Sankey lines are drawn from parent to child rectangles to indicate the hierarchy. Users can click on each rectangle to specify the metric for exploration, and Map View will be updated correspondingly. In the PCP, each block is represented as a line connecting its values in corresponding explicit metrics. The bins in each explicit metric are assigned the same heights. In case bin values of a metric are not of equal size (for example, [0, 0.2], [0.2, 0.3], and [0.3, 1] in GSI), we specially put a gap between consecutive bins to remind users of the inequality. For each implicit metric, we draw a bar chart to indicate its histogram in the corresponding rectangle in the tree diagram, while histograms for explicit metrics are encoded as hollow circles with their area sizes indicating corresponding bin volumes in the PCP (T.2.1).

Figure 3(b) shows an overview of urban design metrics, corresponding to Map View in Figure 3(a). Here, the urban vitality rectangle is selected, as indicated by its light-gray background and colored bar charts. The histogram reveals that the number of blocks in the whole city and urban vitality briefly follows a power-law distribution: As urban vitality increases, the number of blocks drops exponentially.

User Interactions

To support overview and details exploration, VitalVizor integrates the following user interactions:

- *Spatial filter*. Users can specify an area of interest with District, Rect, or Lasso buttons in the Filter panel overlaid on top of Map View (T.1.2). Specifically, if the District button is enabled, users can select one of the districts in a city. After specifying an area, streets, blocks, and buildings outside the area will be colored gray (Figure 5(a)) and Metric View will only display urban design metrics of blocks within the area.
- *Metric focus*. Users can select a set of metric bins as a focus, with others as context, in Metric View. Multiple bins can be focused on at the same time, featuring a series of intersection (∩) operations. In Figure 5(b), the user first focuses on the top two urban-vitality bins, and then further selects an amenity within [20%, 95%], as in Figure 5(c).
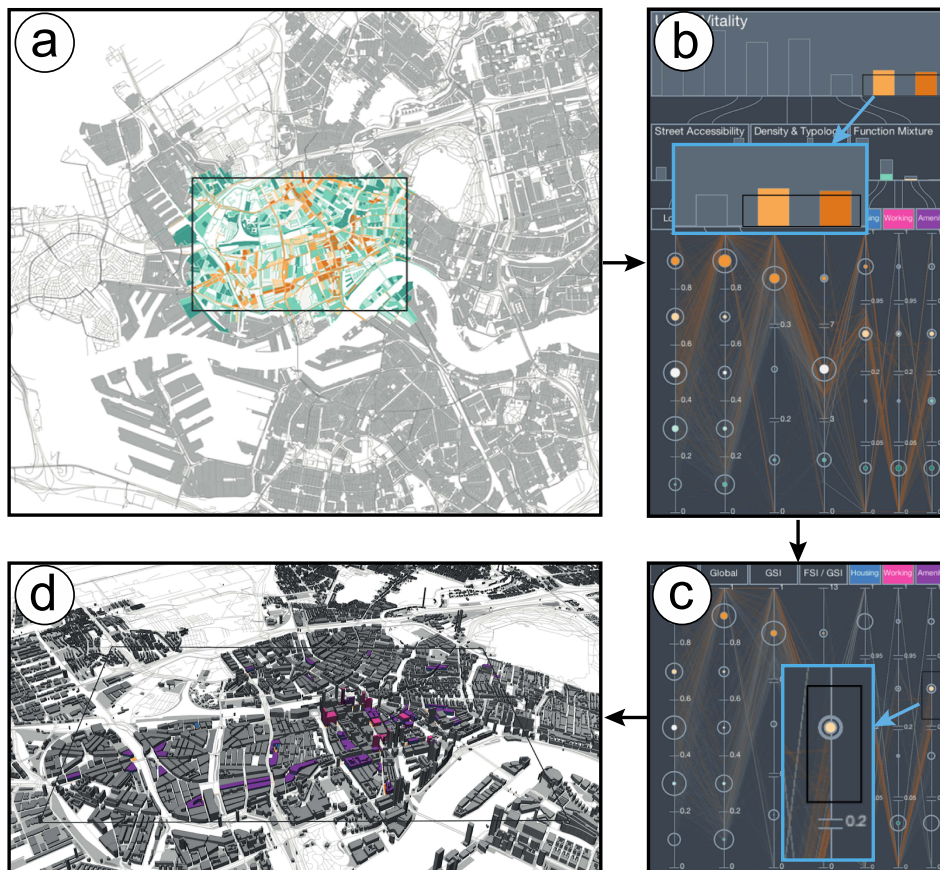

Figure 5. Spatial-filter and metric-focus interactions are implemented. (a) Filtering a central region with the Rect tool. (b) Focusing on the top two urban-vitality bins. (c) Further focusing on amenity in the bin [20%, 95%]. (d) Viewing buildings of interest.

After these spatial filters and metric focuses, the user can visually explore the details, as in Figure 5(d). In addition, VitalVizor allows for exporting the view, such that users can visually compare multiple scenarios.

CASE STUDY

In this section, we first present data and implementation details of VitalVizor, followed by two case studies conducted together with the CA.

Data and Implementation

Data

The built environment currently analyzed in VitalVizor covers Rotterdam, the Netherlands, with 319 km^2 in area and 14 districts. The physical entities consist of 5,000 blocks, 20,000 buildings, and street networks with 142,000 nodes and 157,000 edges. They are all collected from Open-StreetMap (OSM) and thus share a common Cartesian coordinate system. The numbers of nodes and edges are reduced to 23,000 and 33,000 in the reduced graph, respectively. In addition, we collect information on building floors and functions from Rotterdam's official website, and we manually regulate the information utilizing Google Places and Street View images. All information is integrated and stored in shape files.

Implementation

VitalVizor is implemented in the Lightweight Java Game Library (LWJGL), with Map View rendered in OpenGL and Metric View and overlaid buttons realized in NanoVG. The blocks and building footprints are divided into triangle meshes utilizing a built-in OpenGL tessellation algorithm. With all blocks and buildings enabled, there are over 3.2 million triangles in total. The system runs on an Intel Core i7 2 2.8-GHz MacBook Pro with 16-Gbyte memory and an AMD Radeon R9 M370X graphics board. After offline processing of data management and metrics analysis, VitalVizor supports interactive rendering at 60 frames per second.

Study 1: Exploring Districts with Different Urban Vitality

To create vibrant places, urban designers and planners need to understand existing urban vitality in different design sites. VitalVizor offers a primary feature of visualizing urban vitality in a design site and analyzing its urban design metrics. In this study, we use the District Filtering button to specify design sites as two districts: Waalhaven and Centrum. The districts exhibit different urban vitality, and we explore reasons behind the difference.

Figure 6(a) gives an overview of the spatial distribution of urban vitality in Rotterdam. Map View reveals that urban vitality is low at peripheral areas (such as Waalhaven district), while it is high in the central area (Centrum district). Figures 6(b) and 6(c) further present detailed urban design metrics in Waalhaven and Centrum districts, respectively. In Figure 6(b), it is observed that urban vitality is dominated by low values, mainly caused by low street accessibility and function mixture. At the lowest level, we can see that the lines in the PCP are concentrated in few bins for Waalhaven, especially the local- and global-accessibility values. We further select local accessibility and find that the blocks are all green, as in the corresponding Map View, which is very different from the working Map View, which shows mostly high values. In contrast, Figure 6(c) shows well-balanced urban-vitality values in the Centrum district, thanks to better street accessibility and function mixture. Pedestrian behavior, an important indicator for vitality-making, would be more encouraged in the Centrum district. Note that comparison between the two districts is achieved through the Exporting button.

This study clearly unveils the spatial difference in urban vitality between the two districts in Rotterdam. Whether the difference was planned or naturally evolved, Centrum is a more livable district than Waalhaven. The CA deduces that there are two main reasons for low urban vitality in Waalhaven. First, street connectivity in Waalhaven is poor, which obstructs pedestrian behaviors and leads to lower local-accessibility values. Second, Waalhaven lacks proper housing and amenity facilities, which makes the MXI metric the mono-functional type. In summary, there is a lack of coexistence of high street accessibility and function mixture, and thus the district cannot cultivate urban vitality. To make Waalhaven more vibrant, designers need to first consider improving the street accessibility (for example, by building a new bridge that connects Waalhaven to northern Rotterdam).
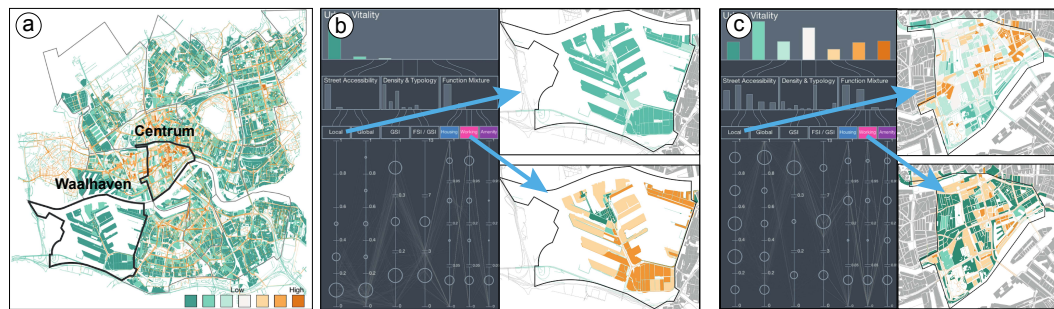
Figure 6. (a) Exploring districts with different urban vitality in Rotterdam: (b) low vitality in Waalhaven and (c) high vitality in Centrum.

Study 2: Identifying Blocks with Imbalanced Metrics for Feasible Improvements

Urban planners and designers need to consider differences among the physical entities in their planning process; a street network has the highest stability of over a hundred years, and a building typically exists for decades, whereas the building functions can be changed relatively more easily. Hence, for blocks with imbalanced metrics, specifically high street accessibility but low function mixture, it is feasible to improve their urban vitality by promoting diverse functions. Designers need to identify such blocks with potential for improvement.

In this study, we first focus on blocks within three intermediary urban-vitality bins, as shown in Figure 7(a). Here, blocks within the two lowest urban-vitality bins have no interest for us, as the low vitality is probably caused by more than low function mixture; blocks within the highest two urban-vitality bins are also off focus, as they are already well-developed. Then, we focus on the blocks with high local accessibility and low function mixture, as illustrated in Figure 7(b), resulting in Map View as in Figure 7(c). A few blocks are identified, and we further filter the area as in the roomed view in Figure 7(c). Figure 7(d) shows the result view with 3D rendering enabled.
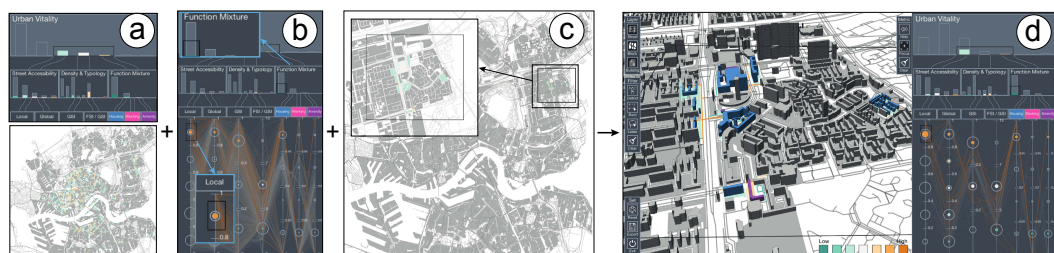

Figure 7. Study 2: Identifying blocks with imbalanced metrics. (a) The middle three urban-vitality bins are focused on. (b) The highest local accessibility and the lowest function mixture are further focused on. (c) Blocks with potential for improvement are identified and filtered. (d) The result view after a series of interactions.

The result view intuitively reveals that these blocks are located beside main streets, while the buildings are all housing type. To improve urban vitality, designers can consider mixing the buildings with working or amenity types. This study illustrates how to identify imbalanced blocks with priority for interventions. With capabilities of spatial filter and metric focus interactions, blocks with other types of imbalanced metrics can also be identified.

EXPERT FEEDBACK

To better understand how VitalVizor can help city professionals achieve better place-making with high urban vitality, we conducted interviews with six independent experts in the fields of

urban planning and design professionals from the Netherlands and China. Two of them are university professors teaching architecture (E1 and E2), and the other four are actively involved in design and planning practices, including urban design companies (E3 and E6), municipal planning departments (E4), and urban planning institutions (E5). E1 and E2 have more than 15 years of experience, while the others have five to 10 years.

Each interview consisted of three parts. First, we started the interviews with a 10-minute brief of the VitalVizor interface by explaining visual encodings and demonstrating user interactions. Then, we showed them the case studies and allowed them to freely explore the system. In the end, we requested their feedback. Four interviews were held face to face at the experts' workplaces, while the other two were held remotely.

Feasibility

All experts showed high interest in VitalVizor and agreed that the tool is well-designed for the specific analytical tasks. They prefer such a dedicated tool, rather than powerful but difficult-to-learn tools, such as ArcGIS. E4 and E6 complained about the steep learning curve of ArcGIS and said that "architects need to write scripts for advanced data analysis, but it is really hard for architects to learn programming." E2 once offered a GIS course to master's students from an urban-design program, but feedback was quite poor, as "the functions in ArcGIS are often in excess of our needs." The experts would like to see more visual analytics systems that are easy to use yet fulfill their analytical tasks.

Visual interface

VitalVizor presents seamless integration of 3D Map View with a 2D analysis view. E4 and E5 preferred the 3D Map View, as "co-presentence of 3D building shape with vitality can only be achieved through the combination of ArcGIS and ArcSense, but they are extremely expensive, and the process is time-consuming." All experts thought that Metric View is intuitive and understood visual encodings immediately with simple explanations. "Simple, intuitive, yet informative," commented E2. Though E5 and E6 only understood PCP after detailed explanations, they felt that more usage scenarios could be identified for the plot in the architecture domain. The experts were not familiar with the overview and detail exploration scheme, but they quickly realized the scheme is similar to the top-down analysis pipeline used in their daily work. E3 and E5 were a bit confused with the metric-focus interaction, but they were convinced by its capacity as demonstrated in Study 2.

Applicability

The experts identified various benefits for their work, as "designing physical entities to create vital and lively urban form is the key concern of contemporary urbanism." First, E1 would like to use VitalVizor for teaching concepts in class—"the Metrics View presented in VitalVizor could help students easily understand the hierarchical relationship among different urban design metrics." Second, E2 through E6 thought the tool could be applied for site analysis. "VitalVizor is quite helpful for identifying problematic and undeveloped design sites," E2 commented. "The tool can help us understand reasons behind low urban vitality and come up with corresponding solutions," said E5. For instance, Study 1 reveals that street accessibility is the bottleneck for low vitality in the Waalhaven district, but improving accessibility would require construction of expensive road infrastructure. In contrast, vitality for blocks in Study 2 can be easily improved through building renovation. Last, E3 further foresaw the potential to apply the tool in design evaluation by comparing designs with present scenarios. "It can contribute to a key issue that we always consider in revitalization projects nowadays: how to make sure the proposed renewal plan is beneficial for a place," E3 added.

Limitations and improvements

The experts pointed out limitations and gave fruitful suggestions for improvements. First, users can only explore urban vitality for an input built environment. They would like to directly manipulate the physical entities to explore "what if" scenarios. Second, VitalVizor computes the design metrics directly, as described previously, limiting its analysis capacity to these defined metrics. They suggested connecting VitalVizor with existing tools, such as depthmapX (https://github.com/varoudis/depthmapX), sDNA (www.cardiff.ac.uk/sdna/), and UNA (https://github.com/zenwalk/urban-network-analysis-toolbox). "To allow users to choose the calculation of design metrics among various kinds of tools can help us better understand which tool is more accurate."

DISCUSSION

VitalVizor is a design-support tool that can assist domain experts for better decision-making in the process of designing lively urban places. The case studies and expert interviews prove the effectiveness of VitalVizor in studying urban vitality. Nevertheless, several limitations exist that are related to our future research directions.

VitalVizor can be applied to any city or district with available input data of the built environment. One frequent request during interview sessions with domain experts was to automatically collect such a dataset, as design and planning professionals prefer to save time on collecting data to produce urban designs. The open urban-data campaign will provide a potential solution, and recently developed data-formatting protocols[7,8] can help derive the measurements directly from the open data. We plan to implement an interface for structured open urban data, such as OSM and Yelp.

At the moment, our system incorporates several explicit metrics that can be directly computed from physical entities of a built environment. Many other urban design metrics (such as street façade) are ignored, yet they are essential for analyzing urban vitality, as well. Planners have identified various aspects of street façade, such as enclosure, greenery, and diversity, as important metrics affecting urban activities. Advancements of deep-learning and computer-vision techniques will generate massive amounts of measurements for these aspects. These measurements will complement the urban design metrics for analysis.

The CA and E1 expressed a strong interest in combining urban design metrics with analysis of dynamic human activities, such as movements and tweets, in VitalVizor. The identified metrics indicate static physical entities, while the ultimate goal for urban planning and design is to improve human lives. They eagerly hope to explore correlations between urban design metrics and human activities. For instance, a recent study shows that extreme events, such as flooding and zonal disturbance, can generate significant impacts on urban flows.[19] Nevertheless, the correlation between human activities and urban vitality should be further investigated by domain experts, and visual analytics tools that allow them to explore the correlations in multi-scale and from multi-perspectives will be necessary.

Nevertheless, adding more analysis functionalities and information layers will be challenging for our system design. Simply adding more coordinated views will bring in scalability issues. To tackle this problem, we should systematically characterize domain problems. For instance, the experts would like to explore "what-if" scenarios, and they should identify these scenarios carefully before implementing. The data should be characterized and structured at the very beginning, as well. These processes require close collaboration and iterative discussions between domain experts and visualization researchers. Regarding designing an exploratory visual interface, we believe the principle of the overview-and-details[18] functionality will still be effective, as demonstrated by the capabilities of spatial-filter and metric-focus interactions in our system.

CONCLUSION

This paper introduces VitalVizor, an interactive visual analytics system designed to facilitate planners' and designers' work in studying urban vitality. VitalVizor is a close collaborative work

between domain experts and visualization researchers. First, we formulated a set of analytic tasks and identified a series of critical urban design metrics through iterative discussions with a CA. Then, we employed coordinated views for presenting both spatial physical entities and non-spatial metrics, integrated with various user interactions for supporting overview and details exploration. Our system is validated with case studies applied in real-world scenarios in Rotterdam, and it received positive feedback from domain experts.

Our research is still in progress. The Discussion section lists possible directions for our future work. When developing the system, we realized that there is an increasing interest in applying exploratory data visualization in urban design and planning. VitalVizor illustrates a response to this emerging trend. We believe such a data-driven and design-oriented interface will become more prevalent in the near future to assist decision-makers in bettering the future of our cities.

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