Computational Support for Interactive Exploration of Urban Design Variants

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Abstract. This research aim is to develop a design support system for interactive exploration of urban space variants. During the early design process for urban masterplan, the design support system can evaluate the state of the design stage quickly and suggest alternative design variants to the designers. Design variants obtained while developing the design concept can be managed to be re-used. Through the management of design information at each design step, a designer can be supported to explore the history of the design process and reuse it. Therefore, it is possible to support breadth-first and depth-first design modes in solution development in a highly structured manner. Therefore, a user can practice informed decision making while preserving ownership during the design process, which can assist designer-led creative design activities.

Keywords: Interactive Exploration, Urban Design, Design Support System, Design Process, Design Management

1 Introduction and Aims

The design activity in conceptual urban design is a complex process for which a designer practices multiple reasoning to solve design problems similar to other design disciplines [1]. Searching for an urban space design that has the potential of providing optimal living conditions is a complicated process in which a designer practices multiple reasoning to solve design problems. As all design problems are not defined in the early stage, a designer cannot identify the correct solutions accordingly [2]. The design problems are usually described as ill-defined, or ‘wicked’ [3] and contains inconsistent specifications, over- or under constrained conditions, and implied information [4]. It is assumed that a designer is often not able to figure out ideal design solutions during a planning process and only examine the quality of the design solutions in a retrospective manner [5]. Therefore, designers explore the design problems and
solution space iteratively, the problem space and the solution space co-evolve until a specific solution is found [6, 7]. In these regards, the focus of this paper is on managing the complex processes of problem structuring: e.g., the exploration and decomposition of the problem, the identification of the interconnections among the problem components, and the exploration of design variants by combining partial solutions [7]. In this paper, exploration implies navigating the problem spaces and solutions spaces within which decision making occurs.

Decision-making activity relies on the cognitive skills of a designer. However, it is inherently biased and error-prone [3] and commonly follows a non-normative behavior, i.e., opportunistic strategies [4]. Moreover, a blind adherent of a designer to an example or initial solutions [5] is defined as a fixation, which is considered undesirable if it confines a designer to a small design problem and solution spaces [8]. Of equal importance, of course, is the diversity of urban design variants during early design stages as well as their performance. It is encouraged to generate diverse and distinctive urban design alternatives, which is likely to add uniqueness to the built environment. An essential part of success is to examine various ideas at the early stage of the idea generation where many different ideas of solution space are explored and measured [9]. After quickly and easily searching and developing solutions using familiar ideas, developing new solutions can be more difficult for a designer. Once an individual is ‘adhered to a set of ideas or concepts limiting the output of conceptual design’ [5], developing feasible design concepts can be hampered by being anchored in the past at the stage of design when creative thinking and actions can bring their benefits [10]. It may confine a designer to narrow solution variants, thus restricting the designer’s creativity [8].

2 State of the Art

In general, the generation of urban structures follows a sequence of several steps: the generation of a road network, the definition of land use areas, and parcel and building allocation [11, 12]. The generation of the road network is accomplished based on L-systems and tensor fields [13]. A popular commercial software, for example, CityEngine, supports the multi-scale (i.e., from a city to a building scale), rule-based planning and modeling [12, 14]. These procedural methods which are based on a set of rules that describe how designs can be synthesized are not related to planning issues; therefore its application to urban design is limited.

A subdivision method to create urban structures is enabled in the City Induction project [15]. In this method, constraints and rules for the generation of urban design have to be specified in advance, and its application to the non-rectangular shape of the plot is limited. The method using DecodingSpaces enables the generation of urban design prototypes by synthesizing spatial configurations for road networks, parcels, and building volumes. A designer can use the tool interactively; therefore, the designer can explore many possible solutions quickly [16]. Layout generation for urban scale is implemented in GIS packages, i.e., ArcGIS in [17].
It is beneficial to examine a variety of design variants before a final design solution is chosen [7]. From this perspective, progresses in urban design computation have been made with fully- or semi-automated design methods [18] in which the designer can be supported for urban layout generation and exploration. i.e. CityEngine, which supports the multi-scale (i.e., from a city to a building scale), rule-based planning and modeling [12, 14], DecodingSpaces [16], and City Induction [15] among others.

However, these entirely-automated or semi-automated generation of the urban space design seems to consider less the human aspects. Moreover, alternative designs obtained while developing the design concept are seldom re-used during the design process. In these regards, we present in this paper a novel approach to encourage a designer’s creative activity by providing the explorative capability for the urban masterplan. Given an urban design task, a designer can place design entities (e.g., buildings, plots, streets) at the intervention site in the urban design support system. Geometric properties of the elements can be manipulated by direct interaction and restrictions for the generation can be modified by indirect interaction. The urban design support system can evaluate the state of the design stage quickly and suggest alternative design solutions to the designers. The concept of the proposed urban design support is that a designer can involve in design authoring activities and the design support system can suggest alternatives quickly as shown in Fig. 1.

![Fig. 1 The overview of the interactive exploration of urban space design](image)

The way in which designers develop solutions to problems is vital for devising techniques for computer-based design support. The main idea of the method is that the designer defines specific parameters and the corresponding urban space configurations are adaptively generated.

In this paper, we will focus on the explanation of i) the methods used for the generation of urban design variants, and ii) methods to explore the design process. We assume that if design variants can help more flexible decision making. Moreover, we try to suggest a method for managing design histories.

### 3 Methods

Most of the above-described methods in CityEngine, which supports the multi-scale (i.e., from a city to a building scale), rule-based planning and modeling [12, 14],
DecodingSpaces [16], and City Induction [15] generate the urban form by first creating the road network and then by generating lots and parcels, which are defined by polygonal regions. In contrast to other urban generation methods which focused on the automated synthesis of a set of possible solutions, we introduce a designer-led design approach which allows more capability to the designer. Some parts of design problem can be solved by using algorithmic methods, but there are still many issues such as social, cultural and economic dimensions that are not yet formulable, which are considered in urban development and regeneration [19].

3.1 Urban Design Variants

The term ‘urban design’ is used to refer to the process of designing urban places. In a narrow sense, urban design engages in manipulating and structuring a decision environment which guides others to author the built environment [20]. The decision environment aims to realize an intended state of the built environment, which is mainly defined by relating urban part to a larger whole [19]. It includes not only physical dimensions but also social, cultural and economic dimensions. Except for all aspects of architectural/building design, the urban design deals with the basic three-dimensional form, massing, and positioning on the plot.

Typologies of the urban configuration that is supported in this research are a block structure and grid structure, which can be extendable to other types of urban layout. Moreover, masterplans are the form of urban design tasks that are used increasingly in urban development and regeneration [19].

Three fundamental methods which are mainly used to relate the parts to the whole, i.e., additive, divisional, and superimposing approaches are defined in [21]. In the additive approach, parts are defined in advance before assembling them into a whole. Whereas, in the divisive approach, the overall form of the whole is defined before the parts. With the superimposing approach, the urban form is generated by overlaying multiple urban patterns. Except for the superimposing approach, our method focuses on supporting the additive and divisive approaches.

3.2 The synthesis method of urban variants

Our synthesis method of urban variants is composed of several functions:

Function 1: First of all, axis lines that represent road networks and a bounding polygon that represents the intervention site are inserted. The designer can modify the axis lines through the design process. All the crossing points along the axis lines and the bounding polygon are identified, which used to generate smaller enclosed areas that represent for blocks. For the extraction of the blocks, the axis networks are converted into a half-edge data structure [22] that is represented as vertices, edges, and faces as in Fig. 2. In this data structure, faces are searched and transformed into their geometric representation as polygons. The use of the half-edge data structure has several advantages. For instance, when representing blocks and districts of the intervention site, the half-edge data structure can provide several utilities: Firstly, adjacent axis lines of the selected axis line can be pointed. Secondly, incident blocks of the selected perimeter
blocks can be pointed. Thirdly, two confronting perimeter blocks that are divided by an axis line can be pointed by selecting the road segment. Fourthly, when a corner node is chosen, blocks that share the corner node can be identified. Fifthly, it is simple to handle all the surrounding road segments of an enclosed block.

**Fig. 2** The basic pointers used to model the urban structure using the half-edge data structure. On the left, the yellow block has a pointer to its neighboring blocks. The boundary of each block is a closed polygon that is represented by using the half-edge data structure.

Function 2: Secondly, a designer can navigate these blocks in order to generate different block layout. Rules to generate different block layout styles are adapted and developed, with which the designer can replace the initial block with, for example, variations of perimeter block style by using i) simple buffer algorithm or ii) subdivision method for partitioning of a block region into small plots. Therefore, depending on the block layout style that is preferred by the designer to support the function of the block, different subdivision approaches are used as in Fig. 4 and Fig. 5.

In case an enclosed perimeter block style is selected, an intervention block is dealt with as a large plot instead of generating many smaller plots as shown in Fig. 3. The unique feature of the enclosed perimeter block style is that the inner courtyard is surrounded by buildings; therefore it can provide open space. For its representation, two offset distances from the perimeter of the block are calculated, the one is the outer polygon that meets roads networks, and the other is the inner polygon that surrounds the inner court. These two polygons are used to generate building layouts which are represented by using the half-edge data structure as well.

By using the half-edge data structure, each building knows its incident buildings; it is possible to design buildings without violating topological relations. It is enabled as buildings have a pointer to their neighboring buildings. For example, the designer can divide a building footprint into several units or merge several buildings into a single unit. Besides, a particular portion of the surrounding building can be omitted in order
to make the block more open, i.e., semi-enclosed perimeter block style. Replacing an initial courtyard with several smaller courtyards is possible by inserting building rows in the inner polygon.

Fig. 3 Building generation based on the enclosed perimeter block style. On the top-left, polygons of the block are created by using axis lines and the polygon of the intervention site. On the bottom-left, footprints of all perimeter blocks are created by calculating buffer distances. On the right, an example of final design outcome, which generates the layout of a perimeter block housing.

The procedure for the subdivision of the block into parcels is as illustrated in Fig. 3. The shape of the block is not always rectangular, so we use the convexity of the shape of the block for preprocessing of the block, minimum bounding box of the block, and Voronoi diagram.

Fig. 4 An example of the application of subdivision method to a convex block in order to make smaller plots. A minimum bounding box of the intervention block is calculated first. Then, dividing lines that are decided by using the pre-defined minimum and maximum size of a plot is
located in the minimum bounding box. Finally, overlapping areas between the polygon of the intervention block and the dividing lines are decided, which can generate plots.

**Fig. 5** An example of the application of subdivision method to a non-convex block in order to make smaller plots. If the polygon of the intervention block is not convex, the block is decomposed into several convex polygons. The rest of the process in order to generate plots follows the subdivision method in Fig. 4. If the size of the plot is less than the pre-defined minimum size of the plot or if the generated plot is surrounded by other plots, a designer can merge these plots into their neighboring plots.

**Fig. 6** A screenshot of the urban design support
Function 3: If the designer wants to generate other design alternatives, different design variants can be suggested to the designer. These generated design variants are kept as case solutions of the working block so that the user can navigate different variants.

Function 4: Moreover, the designer can navigate different design sessions at any times and reuse the sessions to develop design concepts further. This concept is explained in the next Chapter on the human-computer interaction model for the generation of urban space design.

We introduce a new data structure which allows for a more flexible design process contrary to other established procedural methods for urban modeling [14]. For the prototyping of the urban design support, Qt Creator for implementing Graphical User Interface, Boost that is a C++ based open source library for calculating geometric issues such as linear algebra are used. Information that is necessary to keep track of and reuse each design session is managed in MySQL. Fig. 6 show a screenshot image of the urban design support system.

4 Interactive Exploration

![Fig. 7 A concept of the human-computer interaction model for the generation of urban space design](image)

A unique feature of the proposed urban design support is that a designer can involve in design authoring activities and the tool can suggest design variants based on the designer’s queries. Two ideas are introduced to provide a more detailed conceptual explanation. The first activity is called as “Human-Computer Interaction Model” (Fig. 7) and the second activity as “Internal Workflow Model.” The Human-Computer Interaction Model denotes the interactive authoring activity through the interface of the design support system, and the Internal Workflow Model is a backbone that works inside the design support system.

Some effects of the interactive generation of design alternatives are predicted as follows: Firstly, the cognitive processes can be more stimulated through the interaction between the human and design support. For instance, when an individual experiences short-term design fixation which stagnates the design generations, the design support helps make the urban design more active by allowing the search for unexplored problem and solution areas.
Secondly, designers may be more likely to concentrate on more creative activities by saving time for the routine cognitive process. In the design support, specific design subproblems are formulated and used for the automated design generation and analysis. For this, specific rules for design generation are formulated based on case studies. Integrated generation and analysis approach may unburden the designer’s intensive cognitive processing.

Thirdly, infeasible design alternatives, which can be evaluated infeasible in the later design stage, can be filtered out in advance through the design support. As a result, design support can reduce the opportunity cost. Of course, abandoning unique design ideas without enough examination must be avoided. However, possessing many design alternatives, which may be assumed beyond the designer’s capacity, will impose an unnecessary strain on the designer’s cognitive reasoning.

Fourthly, how design alternatives are presented to the user can arguably influence the decision making. The design support can present several design alternatives simultaneously in addition to presenting options sequentially. In some cases, individuals are more likely to select the optimal option with the intent of helping designers make more optimal decisions (Basu and Savani, 2017).

Through the concept of a “design search cycle” model between a user and the urban design tool, how the urban design tool can support multi-level successive design activities will be explained. During the conceptual urban designing where most of the creative design decisions are made, the design process is composed of successive design activities, each of which conducts tasks such as identifying design problems and generating design solutions of the identified design problems. Any design has a start and an end. According to Lawson, different strategies can be adapted or adopted concerning problem formulation and solution generation.

4.1 Urban design problem search

Urban design is to be completed when all the urban problems are solved to an acceptable or satisfying degree. Any means, requirement, issue, value or context that demands a response/solution for an urban masterplan to be successful can mostly belong to the urban problems. The design problems are evoked from a different source of origins. They are sometimes identified by the urban designer while analyzing design facts and can be evoked while developing design solutions. Also, the conceived problem may evoke another design problem(s).

For example, the “access to open space” is quite often admitted as a significant issue of sustainable urban design. Whether this issue is given as a design requirement, or intended by the urban designer, once the issue is perceived as a design problem, the urban designer analyzes it, and a proper solution to respond to the issue is synthesized. The design problem, “access to open space” can evoke relatively related design problems, i.e., “design of open spaces regarding appearance, location and size,” or “efficient use of land and space.” These problems are analyzed, and urban entities with a particular formal solution are synthesized and tested.
4.2 Urban design solution search

During the urban design process, each design problem does not always evoke only one specific solution, but multiple solutions are synthesized until one proper solution will be accepted as a final solution. When an urban designer synthesizes a solution, it is often the case that he or she retrieves a typological concept from a previous case, something from his or her own experience or memory, and solutions are generated to be adapted to the given context by analogical thinking.

For example, after analyzing the design problem such as “access to open space”, the urban designer can synthesize a typical urban structure such as “perimeter block housing with an inner-courtyard” and any other alternative design scheme. These synthesized urban design solutions can often be kept for a long time, and they compete with each other. Alternatively, the competition is sometimes suspended when only one of them is decided to be developed further, or all of them are eventually put away if the designer decides to develop a new concept.

4.3 Urban design episodes

When the period between design start and design end of an urban design project is defined as a design session, which manages multiple sub-problem searches and corresponding sub-solution searches. The design session consists of multiple design episodes [23], each of which is represented by the combination of one design problem search and the corresponding design solution search. A design episode consists of different design activities of the designer to bring up a design problem and to synthesize a design solution to manage the problem.

Fig. 8 An example of a sequence of design progress. The designer can choose a specific block to develop more details by using automatically generated design variants or controlling parameters.
Multiple design solutions for a specific design problem can evolve in parallel. It does not mean the urban designer engages in more than one design episodes at the same time. On the contrary, when a specific design problem gets prioritized at a certain point, the problem search for other design problems are put on hold until they are re-visited as shown in Fig. 9. In this case, the other design problems can be managed in the urban designer’s memory or through other forms such as sketches and written memos. A design problem that is raised or activated at a certain point can successively bring up other problems one after the other before the urban designer. When the designer moves his or her design attention across different design episodes, it is called as ‘design shift.’ The design shift occurs when a completed design episode can evoke other design problem; when a design problem of a design episode evokes other sub-problem(s). Also, the design shift reveals itself when a design episode may be ended only dealing with a specific design problem without a corresponding design solution.

Fig. 9 A conceptual representation of design episodes during a design sub-session. The sub-session is a sequence of design episode. By using the design history management module, it is possible to navigate any design sessions/design episodes and use them to generate new design variants.

4.4 Modeling the problem-solution cycle

The concept of an interaction model between designers and the prototype of the computation support is introduced to represent ‘design search cycle.’ It is based on the notion of the design process as an iterative or recursive search process [25], or self-reflective practice in which designers think in action [26].

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1 The shift of design focus across different design moves are portrayed in a graphical representation “Linkography” in [23], in order to capture the creativity and fixation effect. For details, see: [24].
Through the interaction between a user and the design support, activities for multiple design episodes at the different design level can be competed so that adaptability (i.e. flexible for new problem formulation when an unknown problem situation is discovered) and circularity (i.e. iterative solution-problem co-evolution) can be partially supported, among the essential features that are suggested for an interactive layout design system [27].

By simple authoring actions such as inserting, deleting, and merging an axis line, a user can manage the urban design entities in consideration of urban form and performance. Urban design can use his or her own experience in order to solve design problems. By assigning a priority to urban entities (e.g., freeze an urban block if the user wants to get design solutions of other design entities) for design synthesis which is conducted in the design support tool, more feasible design solutions can be generated without losing the design intent.

As there is no means to detect the user’s design intent for each episode, the design system is to capture events during the design session. In other words, when the design system detects user events as a form of mouse events on the interface level at a particular time, all information of the current working design is saved and managed in the database. In the design system, the design task is progressed through the intervention of the user. Through the management of design information at the later stage, a designer can navigate the history of the design process [28].

Fig. 10 A database table for design history management. During the design process, the urban design support system can push/pull information to/from the MySQL server. A project is composed of design sessions, and each design session is referenced by axis and block tables.

5 Conclusions and Outlook

This research aim is to develop a design support system for interactive exploration of urban space design. During the early design process for urban masterplan, the design
support system can evaluate the state of the design stage quickly and suggest alternative design variants to the designers. Design variants obtained while developing the design concept can be managed to be re-used. We introduce the methods for the generation of urban design variants using the rules, and methods for navigating the design process by managing design history. We assume that the provision of design variants can help more flexible decision making.

As a prescriptive model to overcome some limited aspects of current urban design support, therefore, we proposed a computational support model which allows for interactive exploration of urban design. When a user-led design generation is stagnated, the design support system can suggest design variants, which will enable the designing more efficient. As the form synthesis rules can be applied to each individual urban entities (blocks, plots, and buildings), the designer can change each geometry and manipulate control parameter values.

By automating routine design process, the designer can concentrate on more creative activities. Specific design sub-problems are formulated in advance for the urban design generation and analysis, which may reduce the designer’s routine cognitive processing. Infeasible design alternatives can be screened out in advance.

It is possible to present several design alternatives all together at a specific design session, which can help the designer make more optimal decisions. The design support can present urban design options simultaneously, by which a designer can make a more optimal decision. Through the management of design information at each design session, a designer can navigate the history of the design process and reuse it. Therefore, it is possible to support breadth-first and depth-first design modes in solution development in a highly structured manner. A designer may practice informed decision making while preserving ownership during the design process, which can assist designer-led creative design activities.

As shown in Fig. 1, urban design synthesis rules and evaluation methods which are not covered in this paper will be published in separate papers. The proposed urban design synthesis rules in this paper have to be further developed in order to generate more diverse patterns. Also, evaluation methods such as visibility, openness, density, and connectivity that are commonly used in early design stage need to be incorporated in the design support system.

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