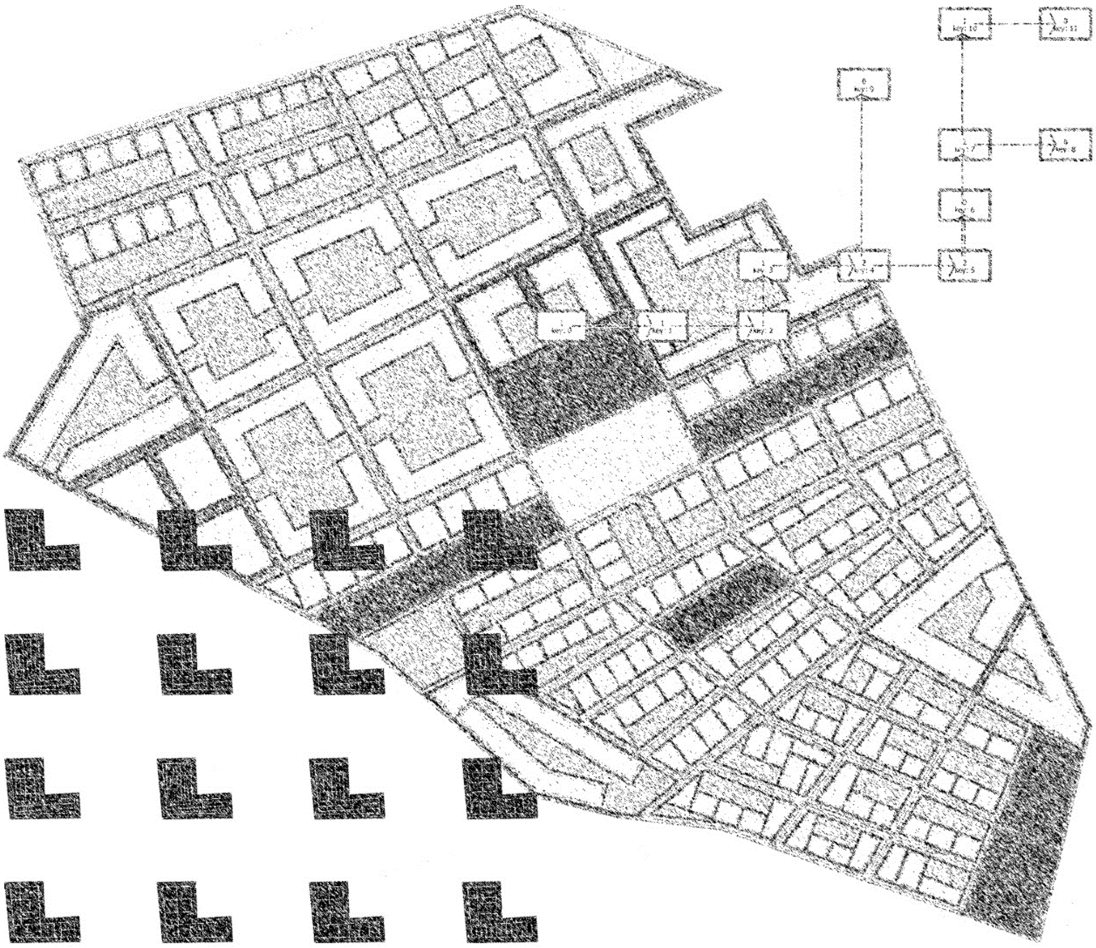

Dissertation

Computational Support for Interactive Urban Design Exploration

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Declaration

Except where otherwise stated and for commonly understood and accepted ideas, this dissertation results from the author's research and does not include the outcome of work done in collaboration. This dissertation has not been submitted as a whole for any other degree or qualification at the Technical University of Munich or any other Institute of Learning.

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Abstract

The early phases in urban design are characterized by the development and evaluation of property and area divisions, building configurations, road networks, and many other urban design factors with the aim of finding the best solution for the urban fabric. Generative or Artificial Intelligence-based design support tools are able to suggest possible solutions but do not support a co-evolutionary design process with the designer. Current generative methods and tools also lack the exploratory component that allows the designer to approach a promising solution iteratively. In practice, in which not all criteria and conditions can be conclusively determined, these tools can therefore only be used to a limited extent.

Within the scope of this dissertation, methods and approaches for the interactive exploration of the problem-solving space are examined. Based on this, a new approach will be developed that supports the exploratory working method of urban design, in which the designer continuously reviews target specifications and incorporates new knowledge into the design in an iterative process. Naturalistic operations such as additive, dividing, and superimposing methods are available to the designer that support the development and transformation of design variants in the context of urban design. Based on the decisions made, design alternatives are proposed to the designer, which are generated through a rule-based synthesis of urban patterns in the urban masterplan. Objectifiable analyses of visibility, density, sunlight, and connectivity are continuously calculated, which enable the designer to evaluate the results. The urban designer can track and adapt design ideas that are generated in a sequence of design steps and, thanks to the "design history," use them flexibly.

An urban design support prototype was implemented and tested using case studies. The approach was evaluated as part of a user study in which test subjects (architects and urban designers) used the prototype to conduct a design task. The proposed methodology was verified on the one hand by means of surveys, and on the other hand, through the empirical analysis of the design results, the extent to which the methodology supports the development of original, high-quality ideas in the early design phases. It is concluded that the proposed interactive co-evolutionary design approach between designers and the design support promotes new and innovative solutions. Following the critical discussion of the results, in which the limits and potentials of the methodology are shown, further questions are formulated.

Keywords: Urban Design Support, Design Exploration, Design History Navigation, Rule-based Layout Generation, Design Creativity

Zusammenfassung

Die frühen Phasen in der Stadtplanung sind geprägt von der Entwicklung und Evaluierung von Grundstücks- und Flächenaufteilungen, Gebäudekonfigurationen, Straßennetzen und vielen weiteren städtebaulichen Faktoren mit dem Ziel die beste Lösung für das Stadtgefüge zu finden. Generative Entwurfsunterstützungswerkzeuge sind in der Lage Lösungsvorschläge aufzuzeigen, unterstützen jedoch keinen koevolutionären Entwurfsprozess mit dem Planer. Aktuellen generativen Methoden und Werkzeugen fehlt überdies die explorative Komponente die es dem Planer erlaubt sich einer optimalen Lösung iterativ anzunähern, in der Praxis, in der nicht alle Kriterien und Rahmenbedingungen abschließend festgestellt werden können sind diese Werkzeuge daher nur bedingt einsetzbar.

Im Rahmen dieser Arbeit werden Methoden und Ansätze für die interaktive Exploration des Problemlösungsraums untersucht. Darauf aufbauend wird ein neuer Ansatz entwickelt, der die explorative Arbeitsweise der Stadtplanung unterstützt, in dem der Designer laufend Zielvorgaben überprüft und neue Erkenntnisse in einem iterativen Prozess in die Planung einfließen lässt. Dem Planer stehen additive, teilende und überlagernde Methoden zur Verfügung die im Kontext der urbanen Planung die Entwicklung und Transformation von Entwurfsvarianten unterstützen. Dem Planer werden dabei basierend auf seinen getroffenen Entscheidungen Designalternativen vorgeschlagen die durch eine regelbasierte Synthese von Stadtmuster im Masterplan erzeugt werden. Laufend werden dabei objektivierbare Analysen zu Sichtbarkeiten, Dichte, Belichtung und Konnektivität berechnet die es dem Planer ermöglichen die Ergebnisse zu bewerten. Der Stadtplaner kann Entwurfsideen die in einer Sequenz von Entwurfsschritten erzeugt werden, verfolgen, anpassen und dank der „design history“ flexibel wiederverwenden.

Ein Prototyp wurde implementiert und Anhand von Fallstudien getestet. Im Rahmen einer Nutzerstudie in dem Probanden (Architekten und Stadtplaner) die Software zur Bearbeitung einer Designaufgabe eingesetzt haben wurde der Ansatz evaluiert. Dabei wurde die vorgeschlagene Methodik einerseits anhand von Befragungen verifiziert, und andererseits durch die empirische Analyse der Entwurfsergebnisse untersucht inwiefern die Methodik die Entwicklung origineller Ideen mit hoher Qualität in den frühen Planungsphasen unterstützt. Es konnte gezeigt werden das der vorgeschlagene interaktive koevolutionaere Entwursansatz zwischen Planer und Software neue und innovative Lösungen fördert. Im Anschluss an die Kritische Diskussion der Ergebnisse in dem insbesondere Grenzen und Potentiale der Methodik aufgezeigt werden weiterführende Fragestellungen formuliert.

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1 Introduction

1.1 Background and Motivation

The second-order design activity (George, 1997, p. 152) in conceptual urban design is composed of complicated processes in which human designers practice multiple reasonings to solve design problems similar to other design disciplines (Dorst, 2011). Design problems contain inconsistent specifications, over or under constrained conditions, and implied information (Ozkaya and Akin, 2006, p. 381); therefore, during a design process, the co-evolution of design problems and solutions executes iteratively (Dorst and Cross, 2001, p. 397). The design problems are usually described as ill-defined or “wicked” (Rittel and Webber, 1973), and it is known that designers cannot figure out undoubtedly correct solutions beforehand; therefore, they often examine the quality of the design solutions only in a retrospective manner (Nikander, Liikkanen, and Laakso, 2014, p. 473). When it comes to urban design, searching for an urban design solution that has the potential of providing pleasant living conditions while maximizing profits is one of the fundamental concerns in the design process. The early urban design process's main activities include the configuration of site layout, buildings, road networks, and other urban entities, which collectively are expected to achieve the urban fabric's best performance. As the quality of urban life is highly dependent on the built environment, a significant concern is placed on finding optimal and promising urban forms. However, it is a challenging task that is not simple to formulate because of the design problem's intrinsic nature.

First, the objectives in urban design may be broadly categorized twofold, e.g., qualitative or quantitative. The former may depend on subjective tastes; among others, intentions of urban designers, socio-economic and aesthetic issues are included. On the other hand, the latter contains issues related to density, i.e., view, daylight, and openness, which can be numerically calculable if the physical characteristics (e.g., volume, dimensions, and layout) of the urban fabric are defined, as will be discussed in Subsection 2.3.2. Once the urban design's physical characteristics are decided, quantitative issues are routinely measured in the later stage of the design process. However, satisfying at least multiple quantitative objectives, or all qualitative and quantitative objectives together, is not a trivial task. Besides, any of these issues cannot be negligible to yield a good urban design. In the worst-case scenario, it fails to prevent the withdrawal of design proposals in the later design stage. Of course, of equal importance is the diversity of urban design spaces during early design stages in practice, not to mention their performance. It is not encouraged to generate monotonous and indistinctive urban design alternatives, which is likely to fail to add uniqueness or identity to the built environment.

Nevertheless, a significant rigidity that is derived from the unconscious application of generative design methodology is frequently witnessed in design cases (Duarte *et al.*, 2012a). Furthermore, a blind adherent of a designer to an example or the designer's initial solutions (Jansson and Smith, 1991) is called 'fixation,' which is considered undesirable because it confines a designer to a small solution space; thus, it can restrict the creative activity of the designer (Tsenn *et al.*, 2014). Furthermore, design problem-solving activity relying on a human designer's cognitive skills is inherently error-prone (Jonassen, 2012; Nikander, Liikkanen, and Laakso, 2014).

Thereof, apparent demands exist to overcome these limitations. It is argued that examining a large quantity and a variety of potential design spaces is beneficial before selecting a design solution that fits their requirements best (Akin, 2001). In this perspective, progress in design computation has been made with fully or semi-automated design methods. Among efforts for the form making and analyses in urban design scale, for instance, layout generation for urban scale is implemented in GIS tools, and various types of dynamic environmental analyses have been available, as will be discussed in Section 2.4.

However, the design support tools that rely on generative or AI-based approaches do not support the co-evolutionary design process, as will be discussed in Section 2.5. Often certain aspects that a human designer should take care of cannot be integrated into the tool. Also, the data from analysis tools are not used to guide and assist the form-making procedure. Moreover, current urban design support methods that will be discussed in Section 2.4 lack the explorative capability of design variants. Consequently, in practice, in which not all criteria and conditions can be conclusively determined, these tools can only be used to a limited extent.

Therefore, to overcome the bottlenecks above, it is necessary to develop a methodology that redeems these weak aspects. A general idea to cope with the request is to develop a computational design support methodology that enables us to explore larger urban design spaces and support design generation. Various types of urban configurations, which are feasible and diverse under a given condition, can be generated in conjunction with computational analysis methods. The proposed methodology can assist human designers' more naturalistic design activity and automate parts of the design process.

1.2 Research Question and Objectives

The preliminary overarching research question that the dissertation addresses is:

"How can the human designer be supported efficiently for the idea generation in an early urban design stage?"

This research question is, however, far too broad to be answered directly in this dissertation. In order to answer the preliminary question, it is required to understand at least three major elements, in which **a)** the 'human designer' who acts on the design (which is discussed in Sections 2.1 and 2.2), **b)** the 'object' that is being designed (which is discussed in Section 2.3), and **c)** the 'method/tool' that is used as a medium by the human designer in order to design the object (which is discussed in Section 2.4) are included. The aspects of these three entities will be discussed in detail in Chapter 2.

After the review of currently proposed urban design methods in Chapter 2, the research focus is narrowed down to the development of generation rules for urban design variants, interaction with the generated urban design variants, and the management of design history. More importantly, methods for the generation of design variants, analysis of design concept, and the navigation of design history are integrated into the urban design support prototype, which intends to help human designers explore and test urban design ideas interactively. This design approach is different from other generative approaches in that a human designer can actively lead the design development by the interactive use of the integrated components. If the utilities that urban design support provides are considered, the research focus can be shifted to how urban design ideas are to be generated and then explored by the human designer to perform the evolving urban design task interactively. Also, investigating how the generated design variants can improve the human designer's design problem solving is worth studying.

Then, the preliminary research question can be changed to the main research question, which is:

"How does the interactive explorative approach help develop urban design ideas?"

This question leads to the research hypothesis:

"The proposed interactive design approach can encourage a human designer to find urban design ideas effectively."

This dissertation investigates methods to support human designers in the generation and evaluation of urban design variants. The prescribed computational urban design support methodology's primary goal is to encourage a designer's creative activity by providing the interactive, explorative capability for the urban masterplan. More specific research questions related to the preliminary research question are derived from a literature review in Chapter 2.

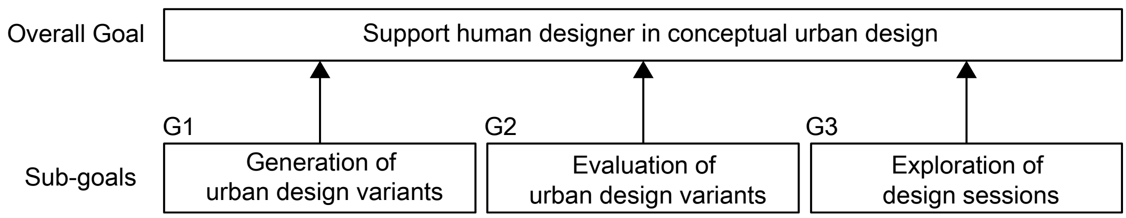

Figure 1 Goals in this dissertation

As shown in Figure 1, more specific sub-goals are presented, all of which pursue the primary goal. The sub-goals are to support the human designer to use the layout synthesis rules for the generation of the urban design variants (G1), the evaluation rules for the selection of appropriate urban design variants (G2), and more importantly, the exploration strategies for the navigation of the design sessions (G3). These supports are to steer the conceptual urban design development process towards purposeful designs.

The proposed urban design support methodology can be utilized as follows: Firstly, given an urban design task, a user (a designer) can place design entities (e.g., street networks, blocks, plots, and buildings) at the intervention site in the urban design support. Secondly, attributes of the urban elements (such as geometric properties, cardinalities, size, and height) can be manipulated by direct user interactions. Furthermore, parameters for urban fabric generation can be modified by indirect interaction. Thirdly, the urban design support can promptly evaluate the design ideas and suggest design variants. Fourthly, the user can flexibly navigate design sessions and reuse design variants that were generated at other design sessions. In particular, the third and the fourth utilities of the proposed urban design support, which is not supported by the currently proposed support for urban design, are expected to provide more flexibility to the human user.

The following four contributions are expected:

The first expected contribution is to support the human designer during conceptual urban design development through the systematic generation and analysis of urban design variants. During the evolution of the design process, geometric and topological information between urban entities is managed thoroughly under user interactions, such as deleting and merging urban entities, which allow for the efficient use of computing resources. Therefore, it becomes more efficient to generate and analyze urban design variants of the intervention area, which can stimulate the human designer for creative problem solving by reducing repetitive work.

The second expected contribution is to support the human designer in selecting an appropriate urban design variant. If the human designer requests design variants that might fit the current intervention area, a rule-based design generation module can suggest a number of new design variants to the human designer concurrently. This approach can allow human designers to compare the design variants and help them improve decision-making.

The third expected contribution is an explorative capability that allows the human designer to navigate design history and flexibly reuse design knowledge that was generated previously. The information of design sessions that have been worked on is visualized to the human designer as a graph network, which allows for easy access to the design information. For example, this approach permits the human designer to put aside the current working design at any time and recall what was developed previously in order to develop a new idea. Moreover, design information that is generated during the evolution of the design process can be managed without substantial loss. It can relieve the human designer's intense memory management.

These contributions are realized as a design support prototype that assists the human designer in rule-based, interactive urban design. The prototype is developed by using open-source libraries and the author's own libraries. Upon request, researchers who are interested in the developed prototype can access the author's libraries of their prototype and further extend it to support other relevant urban design issues. This open-source software policy can help create an ecosystem for urban design software and impact the dissemination of the scientific achievements of this dissertation.

1.3 Research Methodology

This dissertation adopts the main steps – Research Clarification, Descriptive Study I, Prescriptive Study, and Descriptive Study II – which are defined in "*Design Research Methodology (DRM)*" by Blessing and Chakrabarti (2009) as shown in Figure 2.

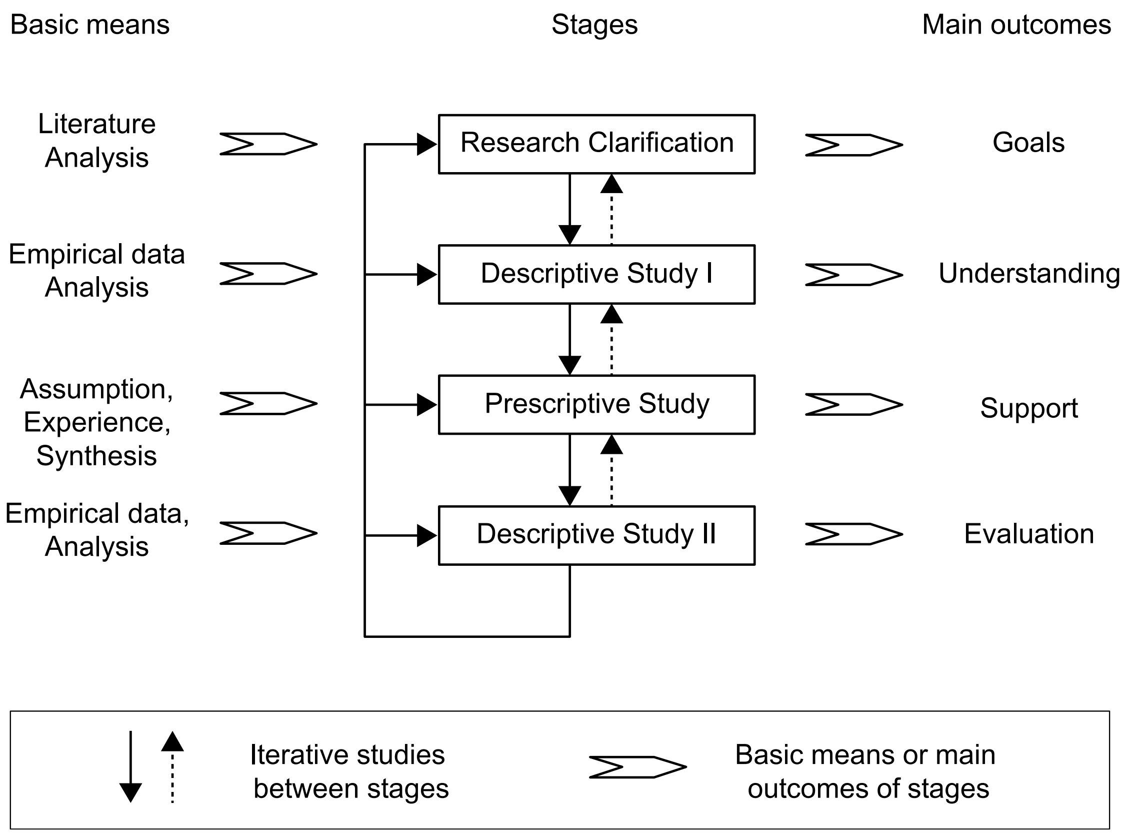

Figure 2 Research methodology used in this dissertation (Blessing and Chakrabarti, 2009, p. 15)

First, the research task is identified in the present chapter (i.e., Research Clarification). Through a literature review on the related works, existing issues of the design support in urban design are further analyzed and clarified in Chapter 2 (i.e., Descriptive Study I). As a Prescriptive Study, a methodology to support human designers using interactive urban design methods is developed in Chapter 3 and Chapter 4. For the verification of the proposed methodology, three case studies, the design experiment, and the design experiment's analysis are conducted, as will be presented in Chapter 5, Chapter 6, and Chapter 7 (i.e., Descriptive Study II). Finally, the contributions and limitations of the proposed methodology for supporting interactive exploration of urban design are discussed in Chapter 8. This research is conducted in a recursive manner, which includes several iterations and parallel executions in different stages, as suggested by Blessing and Chakrabarti (2009). Finally, the outcomes of each phase are addressed in the remainder of this dissertation.

1.4 Structure of the Dissertation

The motivation and aim for the computational support for the interactive exploration of urban design are presented in **Chapter 1**. The structure of the remainder of this dissertation, as shown in Figure 3, is as follows:

In **Chapter 2**, human designers' approaches to problem-solving and issues of design creativity are discussed to support the conceptual design for urban master-planning. Rule-based computational approaches to urban design are discussed in detail since this dissertation's scope is to support human designers using interactive urban fabric generation methods. Recent applications and urban layout generators are presented, and the interaction between human designers and the computational methods is addressed. Challenges for urban layout rule development and application are identified. Related information is given as far as required to understand the concepts used in this dissertation.

Chapter 3 prescribes the methodology for supporting rule-based urban synthesis, so-called interactive urban design support. First of all, a generic framework is proposed to support the interactive exploration of urban design. The fundamental rules that synthesize several representative urban fabrics are introduced in detail after the explanation of the design support framework. The interactive design support enables to **a)** analyze the quality of visibility, density, connectivity, and sunlight that are included for quantitative evaluation of urban form, and **b)** generate design variants by the application of urban fabric synthesis rules. The method is targeted at supporting the interactive exploration of urban design variants. The available options for urban generation, analysis, data visualization, and possible user interactions are presented.

Chapter 4 prescribes strategies to interact with the urban design support and explore different urban design ideas. The generation and visualization of urban design ideas allow the human designer to compare the generated urban design ideas intuitively. These supports can lead to fast decision-making by the convergence of the quantitative and qualitative evaluation simultaneously. Besides, understanding how strategies for navigating design episodes that are generated at each sequence of design steps allows the human designer to select an appropriate one for a given urban design task more flexibly.

Chapter 5 presents three case studies to demonstrate the application of the interactive explorative methodology for urban design and shows that the interactive explorative methodology can be appliable to produce promising urban design concepts in the early design stage.

Chapter 6 presents the experiment settings to verify the prescribed methodology. The description of an urban design task that may be achieved by using the urban design support prototype is introduced, and the adapted experiment procedure is presented. For the evaluation of design outcomes, a measurement method for creativity and evaluation procedure are presented.

Chapter 7 analyzes the evaluation results from the design experiment and discusses why such results are obtained in consideration of the research questions and hypothesis.

Chapter 8 concludes this dissertation by highlighting the main research contributions and limitations of the computational support for interactive exploration for urban design and discussing future works.

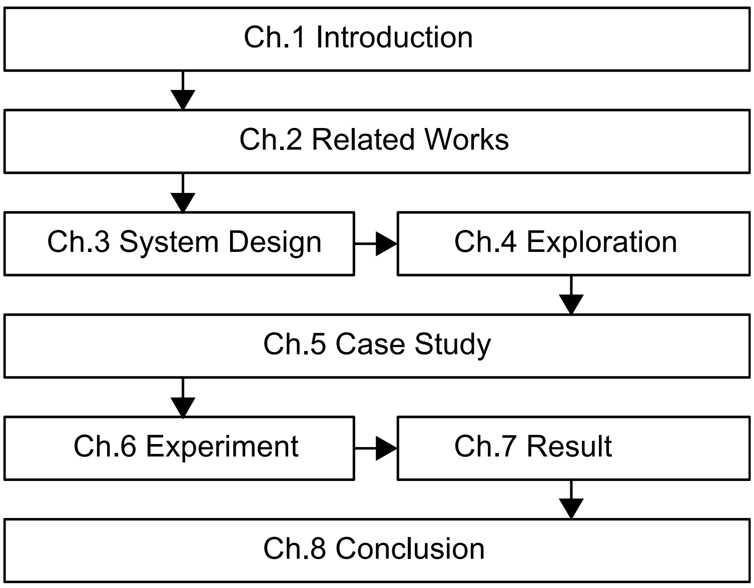

Figure 3 The structure of the dissertation

2 State of the Art

This chapter aims to provide an overview of state-of-the-art design thinking and methodology, focusing on the designer's approaches to design problem-solving. Based on this analysis, I will identify their limitations, which can be addressed by a computational design support method. In order to understand the human designers who act on the designing, approaches for design problem solving are analyzed based on the extensive literature review in Section 2.1, which can help identify the characteristics of the human designer. Limitations of the human-led design approaches and methods to tackle these limitations are discussed in Section 2.2. Subsequently, in Section 2.3, urban design, which is a thematic focus of this dissertation, is summed up, relating to the issues of urban design and the process. Section 2.4 deals with the analysis of the computational tools that support urban design. As a result, the limitations of the current design supports are identified in Section 2.5. In each section, outstanding questions that are relevant to the critical academic questions are posed and discussed.

2.1 Approaches to Problem-Solving

A research question in Session 2.1 is related to the approaches that the human designer uses for solving design problems. *What kind of strategies do human designers use during the design process?* In order to answer this question, the historical background in the research on design thinking and methodologies needs to be discussed. An extensive body of research on problem-solving and decision-making in design exists (Lawson, 2006; Visser, 2006). In particular, Rowe (1994) provided a systematic account of the process of designing in architecture and urban design. Schon (1983) described the behavior of designers in action by analyzing how professionals go about solving problems. Cross (2006) suggested underlying patterns of how designers think and act, or the '*designerly ways of knowing*.' These seminal works have contributed to understanding the nature and cognitive processes of human design activity.

The major purpose of the study on design methodology since the 1960s is to "*develop systematic external methods and tools to carry out the logical analysis better and to unburden the designer to engage in the creative aspects of problem-solving*" (Cross, 1984, referred to in Goel and Pirolli, 1992, p. 397). Significant contributions since the design methodology movement have been made, and the characteristics of design activities are more clearly analyzed, which could improve the design methodology. However, the development of design support based on the findings, which is the primary concern of this research, has remained an open area in the domain of urban design. Here, aspects to support designers during the urban design process will be identified by analyzing strategic approaches in design solution development.

In order to describe a designer's approaches in the design process, to begin with, it is necessary to define an acceptable level of the conception of design. Goldschmidt considered "*the solidification of a major idea, or combination of ideas, that could bring together all the major aspects the design had to respond to*" (2014, p. 44) as the most crucial thing in a design process. The design is characterized as "*a purposeful, constrained, decision making, exploration and learning activity*" that operates within "*a context which partially depends on the designer's perceptions of purposes, constraints and related contexts.*" (Gero, 1996, p. 435). To be more specific, decision-making implies "*the selection of one or more beneficial or satisfying options from a larger set of options*" (Jonassen, 2012, p. 343). Of course, the design options may consist of requirements, predictions, and opportunities, but the decision always requires "*a commitment to a course of action that is intended to yield results that are satisfying for specified individuals*" (Yates, 2003, p. 24).

According to Yates and Tschirhart (2006, pp. 422–423), there are several major decision varieties, including: "*choices*," which entails the selection of a subset from a more extensive collection of alternatives; "*acceptances/rejections*," which is a binary choice in which only one specific option is acknowledged and must be accepted or not; "*evaluations*," which are statements of worth that are backed up by commitments to act; and "*constructions*," which are attempts to create ideal solutions using given available resources. Exploration here implies navigating the problem spaces and solution spaces within which the decision-making occurs. Learning indicates the acquisition of knowledge and its structuring into knowledge structure. In short, decision-making, exploration, and learning in designing seem to be essential for most creative design activities. Based on the definition of the design process and decision-making, Subsections 2.1.1, 2.1.2, and 2.1.3 provide a more detailed analysis of design approaches.

2.1.1 Prescriptive and Descriptive Design Approaches

The notion of the designing activity contains two compatible conceptions of design: the one identifies the designing activity as a form of problem-solving (Goel and Pirolli, 1992) and the other as a decision-making endeavor (Akin and Lin, 1995). Researchers who view design activity as a form of problem-solving tend to highlight the complex and ill-defined nature of design tasks. The ill-defined problems that designers manage are typically described as 'wicked' problems, as shown in Table 1 (Rittel and Webber, 1973). For example, these wicked problems cannot be definitely formulated at the onset, and the quality of the solutions cannot often be assessed right and wrong (McCall and Burge, 2016). Besides, a solution to a problem triggers other problems iteratively. As it is, the focus moves into the issues of how to manage such complexity through the cognitive processes of problem structuring: e.g., an exploration and decomposition of the problem (including the clarification of requirements and constraints); and identification of the interconnections among the problem components; and the exploration of solution ideas by the combination of the partial solutions (Goel and Pirolli, 1992, p. 397).

Table 1 Ten properties of wicked problems (Farrell and Hooker, 2013; Rittel and Webber, 1973)

i.	There is no definitive formulation of a wicked problem.
ii.	Wicked problems have no stopping rule.
iii.	Solutions to wicked problems are not true-or-false but good-or-bad.
iv.	There is no immediate and no ultimate test of a solution to a wicked problem.
v.	Every solution to a wicked problem is a 'one-shot operation'; because there is no opportunity to learn by trial-and-error, every attempt counts significantly.
vi.	Wicked problems do not have an enumerable (or an exhaustively describable) set of potential solutions, nor is there a well-described set of permissible operations that may be incorporated into the plan.
vii.	Every wicked problem is essentially unique.
viii.	Every wicked problem can be considered to be a symptom of another problem.
ix.	The existence of a discrepancy representing a wicked problem can be explained in numerous ways. The choice of explanation determines the nature of the problem's resolution.
x.	The planner has no right to be wrong.

On the other hand, other researchers (e.g., Akin and Lin, 1995) who advocate the view of designing as decision-making focuses on the processes associated with the generation, evaluation, and selection of design solution options. This view conjectures that designers are rational and follow canonical decision-making. However, the stages of such a view can be distinguished only in theory as distinct activities: designers tend to analyze problems and elaborate solutions in parallel, rather than in separate, consecutive stages (Dorst and Cross, 2001), which is not like the way that normative decision making prescribes. Moreover, current evidence on design decision-making confirms that designers are susceptible to making biased decisions and following non-normative approaches (Stanovich and West, 2000). It is an exciting and challenging aspect that can be found in a human designer's approaches.

Also, it is necessary to discuss the aspects of how designers explore design problems and solution space. In the design solution process, designers exhibit top-down, breadth-first design approaches, which is widely advocated as one of the key methodologies for optimum design practice, for example, in software design (Wirth, 1971) and engineering design (Pahl *et al.*, 2007). One of the merits of applying the proposed top-down, breadth-first design strategy is known that such a strategy can attenuate the designer's commitment to existing solution ideas until all sub-problems have been explored at a certain level of detail (Ball, Maskill, and Ormerod, 1998, p. 214). In relation to the top-down, breadth-first design strategy, the "*Limited Commitment Mode (LCM) control strategy*" (Goel, 1995; Goel and Pirolli, 1992) can be acknowledged as a similar notion in a certain sense. In a descriptive study on cognitive processes during design problem solving from protocol data (Ericsson and Simon, 1999) of expert designers in mechanical engineering, industrial design, and architecture, it is identified that "*Limited Commitment*

Mode (LCM) control strategy," which is similar to Stefik (1981)'s "least-commitment" control strategy, is used (Goel, 1995; Goel and Pirolli, 1992). LCM control strategy is explained in Goel (1994, p. 63) as "*while working on a particular module, the designer is not required to complete that module before beginning another. Instead, one has the option of putting any module on 'hold' to attend to other related or even unrelated modules and returning to the first later.*"

On the contrary, pieces of evidence from the protocol analyses associated with software design and engineering design at the expert level showed that so-called opportunistic behavior is abundantly evident, which indicates a deviation from top-down, breadth-first design (Guindon, 1990a, 1990b). Controversially, it is argued that expert designers may selectively alternate the breadth-first and depth-first modes in the solution development in a highly structured manner. Additional remarkable supporting research on the opportunistic behavior of designers was performed by Akin (1986). In an experiment on how designers structure their search domains, Akin (1986) found out that they search breadth-first along with the principal options, then develop one of the options in detail, depth-first, until all design categories are tested. According to the descriptive or naturalistic decision-making models, designers are seldom rational as normative models assume when they actually make decisions. Rather than either the breadth-first mode or the depth-first mode is dominant through the design progress, alternating both modes are identified in a seminal experiment aiming at expert-level engineering design tasks (Ball and Ormerod, 1995), which will be discussed in detail in Subsections 2.1.4 and 2.1.5.

In summary, it is identified that designers exhibit dynamic behavior during decision-making, exploration, and learning activity and apply different design strategies such as opportunistic behavior. In the following Subsection 2.1.2, I want to identify some critical aspects of the co-evolution process as design problem-solving, which can be supported within the computer-aided design environment.

2.1.2 Co-Evolution of Problem and Solution Spaces

To begin with, what makes the design process unique is that it involves finding appropriate problems, as well as solving them. As shown in Figure 4, design cognition is often modeled as an alternating search process across design problem space and design solution space (Dorst and Cross, 2001, p. 435). For creative design, searching for a good solution concept does not seem to come after fixing a problem entirely. What matters in a creative design lies in developing and refining both the problem formulations and solution ideations together (Dorst and Cross, 2001, p. 434). Therefore, the design includes substantial activities such as problem structuring and formulating, rather than merely accepting the '*problem as given*' (Cross, 2001, p. 81). Through the activities, therefore, the designer's view of the problem and solution dynamically co-evolves and changes while the designer interacts with the task (Schon and Wiggins, 1992). Also, human designers constantly generate new goals and redefine constraints that were defined previously. Through such a dynamic process, new features, properties, and other relevant aspects can emerge and affect the evolution of the design. In addition, it is claimed that the designing process starts with an exploration of the problem space (Goel and Pirolli, 1992, p. 397). It is widely acknowledged that the formulation of design problems can only be regarded as a kind of ill-defined problem. After articulating an initial set of constraints and functional specifications, designers make decisions about the designed object based on problem constraints and their personal preferences. Also, the context[1] within which designers act can affect the design process.

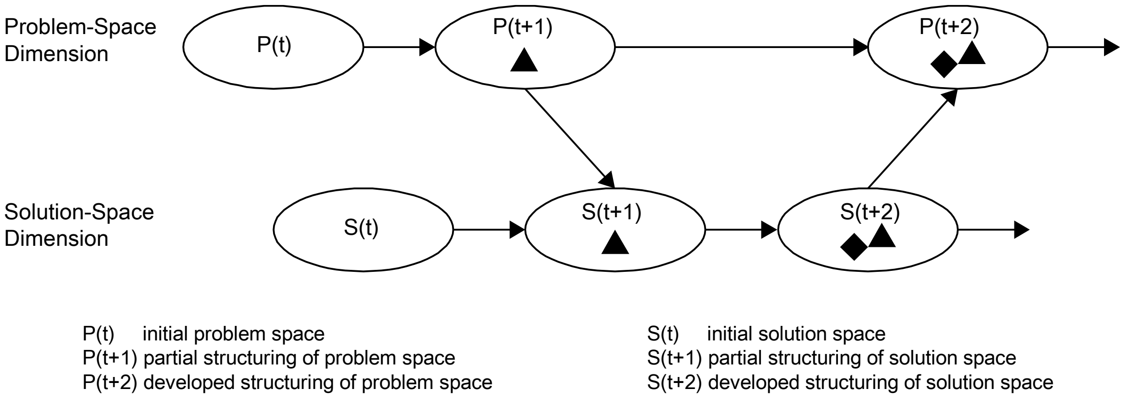

Figure 4 Co-evolution of the problem–solution as observed in Dorst and Cross (2001, p. 435)

It is because designers frequently have to decide with incomplete information and deal with ill-defined requirements and wicked problems (Buchanan, 1992; Rittel and Webber, 1973). Therefore, the design is a "satisficing" activity such as accepting "good enough" solutions, rather than an optimizing and calculating activity, that is, to calculate the optimum value or to select the best solution among all possible solutions (Simon, 1996). Of course, specific design problems in engineering domains can be formulated at the beginning, and an appropriate optimization method can be applied in order to find the best solutions. However, many problems in architecture and, in particular, urban design consist of many aspects, which are gradually recognized, and well-known optimization methods to specific subproblems can only be applied preferably at a later stage. Even these aspects are essential parts that constitute the design process, but they are hardly supported in current CAD tools for urban design. *How can the explorative activity in which the design problem and solution co-evolve be supported?* In order to address this question, it is necessary to understand how the human designer explores design solutions.

[1] For example, Gero and Kannengiesser (2004) adopted the concept of the '*situatedness*' to explain how the interaction of the designer and the task environment determines the course of designing.

2.1.3 Exploration of Alternative Solutions in Design

The designing activity involves complex cognitive processes that require designers to iteratively explore the design problem and solution space and generate a variety of choices for pursuit (Dorst and Cross, 2001, p. 434). In concept generation, both the divergent thinking for creating choices to consider and the convergent thinking for narrowing and selecting from those choices are repeated until eventually determine a final design (Yilmaz and Daly, 2016, p. 139). Similarly, Guilford's research works exhibited that creativity plays a vital role in design thinking, which encompasses, namely, a convergent mental process and a lateral mental process (Guilford, 1967). Therefore, examining various ideas is considered an essential component of success where many different ideas of solution space are explored and measured (Yilmaz and Daly, 2016, p. 139).

While exploring solutions, designers rely on a large number of alternatives and continue to search for alternative solutions even when satisfactory ones have already been developed (Akin, 2001, p. 121). Until a range of options has been fully explored, well-established prescriptive design methods within the engineering domain, such as Pahl *et al.* (2007), advise refraining from committing hasty decision-making, such as choosing an initial (premature) solution idea for a problem or sub-problems. The justification behind the principle of multiple solution searches that the prescriptive design literature espouses seems to relate to the cost of a design decision, i.e., minimal commitment in design. If design decisions turn out to be misconceived in the later design stage, the sunken cost can be extremely high. Therefore, it is advisable to explore a range of ideas before making decisions for a specific problem or subproblems.

However, such an idea that designers should generate and evaluate a range of solution alternatives during the design process is challenged by the facts that (i) "*the space of possible solution concepts is typically very large*," and (ii) "*important design requirements may be nonquantifiable*" (Ball, Maskill, and Ormerod, 1998, p. 216). Therefore, exploring the solution space is computationally intractable and not open to optimization via mathematical methods (Simon, 1996). Human designers' solution search is not considered an optimizing one; therefore, it is impossible to attain optimal design solutions. Instead, they often tolerably explore the entire search space until they accept design solutions to problems in their hands.

Findings derived from different design domains support the fact that human designers often fail to pursue alternative solution ideas (Adelson and Soloway, 1985; Ullman and Dietterich, 1987; Ullman, Dietterich, and Stauffer, 1988). In a work by Ullman and Dietterich (1987), it is observed that designers mainly pursue only a single design proposal. The observed minimal solution search in design may be explained theoretically. One of the persuasive hypotheses explaining this observation is that *"multiple proposals (especially detailed proposals) are too complex to be handled well by human designers*" (Ullman, Dietterich, and Stauffer, 1988, p. 45).

Arguably, with the relatively small human information processing system, compared to the computational resources available for optimization, it may be difficult for human designers to keep multiple alternatives due to the complexity in managing the generated alternatives (Ball, Maskill, and Ormerod, 1998, p. 223). Evidently, it seems that designers seem not to pursue the search for multiple solution alternatives. As such, it is argued that designers may strategically avoid generating and exploring multiple solution alternatives.

The designers spend efforts to make their chosen solutions adequate. Once the original design concepts are evaluated, different operators can be invoked by the designer. For example, if a human designer finds original design concepts inadequate in the later design stage, they may be rejected or fixed. According to the observation of Ullman *et al.* (1988, p. 46), the weakness of the original design concepts is often made up for by applying a valid '*patch*' or even highly implausible patches in order to make it adequate, rather than abandoning them and developing a new better concept (Ullman, Dietterich, and Stauffer, 1988, p. 46). Through the act of patching, the designer can evidently alter design ideas, constraints, or strategies at the same level of abstraction. Moreover, the designer repeats the refinement operation to design ideas, constraints, and strategies to elaborate on more detailed abstraction levels.

Similarly, in a sketch-based design process research on architecture designs, Goel (1994) identified two salient shape transformations in problem-solving phases: lateral and vertical transformations. Lateral transformation means an activity of converting one idea into a slightly different idea; on the contrary, vertical transformations denote an activity of manipulating one idea into a more detailed version of the same idea. Goel's research identifies that designers generate a single idea or a few related ideas and develop them through such transformations rather than generating independent ideas (Goel, 1995), which will be further discussed in the following two Subsections.

2.1.4 Two Modes in Creative Thinking

Let us start with the definition of creativity. Mayer (2014, p. 450) defined creativity: "[…]*creation of new and useful product including ideas as well as concrete objects*." Ideas can be generally considered creative if they possess two main qualities: appropriateness and originality (Sternberg and Lubart, 1999). As such, artifacts solely with high appropriateness or solely with high originality cannot be considered creative. Therefore, when designing a new urban fabric, it can be accepted as creative if the proposed one is both appropriate and original (Amabile, 1983; Shah, Smith, and Vargas-Hernandez, 2003), which are adapted as a creativeness measure in Section 6.3. Regarding creativity, thinking processes that lead to creative outcomes receive much attention. Notably, two systems of reasoning, indeed two modes of thought (roughly convergent and divergent), have been used to account for creative thinking, as shown in Table 2.

Mode-1 is characterized as intuitive and fast, and Mode-2 as logical and deliberative, so each roughly corresponds to divergent thinking and convergent thinking in design problem-solving.

Table 2 Two modes of thought in creative problem-solving

Mode-1	Mode-2	References
Divergent production	Convergent production	Guilford, 1950, 1967
Lateral transformations	Vertical transformations	Goel, 1994
Ideation	Evaluation	Basadur, 1995
Divergent insight	Convergent insight	Finke, Ward, and Smith, 1996
An associative, similarity-based system: making use of visuals	A symbolic, rule-based system: specifying rationale	Sloman, 1996
Associative thought: intuitive, divergent	Analytic thought	Gabora, 2010
Defocused attention	Focused attention	Martindale, 1999

Of course, different terms have been used to describe the two modes of thought in creative thinking. Below, I will provide a comprehensive explanation of two modes of thought in creative problem-solving:

- As can be viewed as an initial, contemporary dual-process model of creative thinking, Guilford initiated the notion of productive thinking within his structure of intellect model, which distinguished between convergent and divergent thinking processes (Guilford, 1950, 1967); the former which can generate one correct solution, and the latter which goes off in different directions, searching for multiple possibilities. He has concluded that "*creative thinking cannot be equated with divergent thinking*" (Torrance, 1995, p. 69).
- As discussed above, Goel (1995, p. 119) proposed that solution search may be fully described in terms of lateral and vertical transformations. He identified supporting evidence for both transformations in the protocol of a practicing architect. Moreover, Goel's study suggests that designers generate a single idea or a few related ideas and develop them through transformations.
- Basadur (1995) proposed that idea generation and idea evaluation alternate during the creative thinking process. He distinguished between three major stages (i.e., problem-finding, problem-solving, and solution implementation) in the creative-thinking process. During ideation, which can be defined as option generation without evaluation, all judgemental, rational, and convergent thinking is deliberately deferred in favor of nonjudgmental, imaginative, and divergent thinking. Contrarily, evaluation is defined as the judgemental application to the generated options (Basadur, 1995, p. 64).
- Finke (1995) differentiated between divergent insight and convergent insight, based on divergent and convergent thinking (Mednick, 1962). Divergent insight occurs when one finds

novel uses or implications for an existing structure. Insight problems that are likely to involve sudden insight tend to involve convergent insight. Besides, Finke, Ward, and Smith (1996) carried out a series of empirical studies and developed a cognitive model of creative thinking called the "*Genoplore Model*," which divided the creative thinking process into two phases: generative and exploratory. Generative phases involve retrieving items from memory, associations between items, and synthesis and transformation of forms to construct ideas' representations. Explorative phases can involve identifying the attributes of these forms and considering their potential functions in different contexts.

- Sloman (1996) emphasized a distinction between two kinds of reasoning systems: 'a quick, associative or similarity-based system' and 'a deliberative, rule-based system.' The associative system utilizes visuals when relevant; as in design, the rule-based system specifies rationale. Besides, Sloman (2012) proposed that type-1 thinking is based on personal knowledge and similarity-based (using visuals) computations, but rule-based (specifying rationale) computation drives type-2 thinking.
- Martindale (1999) identified characteristics related to creativity in terms of focusing/defocusing attention. He suggested that divergent processes involve associative thinking. The associative thinking results from a defocused attentional state, which helps combine items encoded in memory with information from the current context in a state of defocused attention. In contrast, controlled analytic thinking requires focused attention and is thought to predominate in the refinement and evaluation of solutions (Gabora, 2003; Martindale, 1999).
- Gabora (2010) attempted to synthesize experimental and theoretical work on creativity and memory activation; and concluded that creative thinking involves two modes of thought: divergent (or associative) thought and convergent (or analytic) thought. The divergent or associative thought tends to be intuitive, unconstrained, and "*conductive to unearthing remote or subtle associations between items that share features or correlated but not necessarily causally related*" (Gabora, 2010, p. 2). Contrary to divergent or associative thought, convergent or analytic thought is a rule-based or analytic mode of thought that is "*conducive to analyzing relationships of cause and effect between items already believed to be related*" (Gabora, 2010, p. 3).

So far, descriptions of the two modes of thought in creativity are provided, and they may be seen roughly as divergent thinking and convergent thinking. A considerable body of research suggests that creativity involves not just divergent thinking but also convergent thinking. For example, Howard-Jones and Murray asserted that "*most descriptions of creative problem solving thus involve both focused analytical processes and a less-focused generational process, which allows access to remotely associated concepts. Analysis ensures appropriateness, and the inclusion of* *remote elements supports originality*" (Howard-Jones and Murray, 2003, p. 153). Basadur (1995) also suggested that both ideation and evaluation are involved at each stage in varying degrees.

Similarly, Sloman (1996) affirmed that both similarity-based and rule-based systems serve complementary functions and can simultaneously generate different solutions to a reasoning problem. In his own words, "*A different sort of complementarity is that associative paths that are followed without prejudice can be a source of creativity, whereas more careful and deliberative analyses can provide a logical filter guiding thought to productive ends.*" (Sloman, 1996, p. 18). Gabora asserted that, according to the situation given, the flexibility to spontaneously shift back and forth between the modes (i.e., divergent or associative thought and convergent or analytic thought) is essential to creativity (Gabora, 2003). In the following Subsection, various implications of divergent and convergent thinkings in creative design will be discussed.

2.1.5 Divergent and Convergent Thinkings in Creative Design

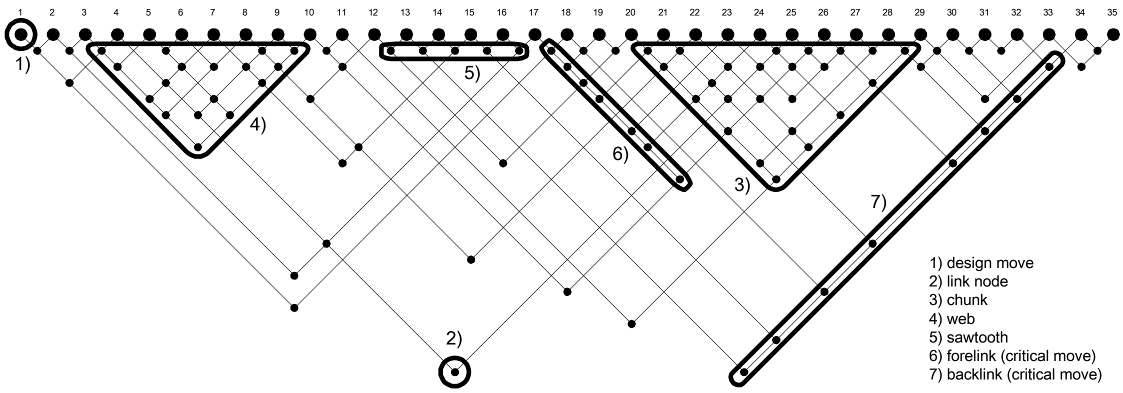

Figure 5 An illustration of features and terminology in linkograph (drawn based on Goldschmidt, 2014)

In design studies, there are several empirical pieces of evidence that creative thinking involves repeated cycling between the two modes of thinking. Two crucial constituents of designers' activity are "*shifting the focus of attention*" and "*exploring related ideas*" (Suwa and Tversky, 1997, p. 395). Concerning the study on design move and shift, Goldschmidt came up with a design analysis method that focuses on recording the transitional process of design work and evaluating the outcomes drawn from the transitional process (Goldschmidt, 1990).[2] So-called linkography was developed as "*a system of notation and analysis of design processes that focuses on links among design moves (or design ideas, or decision)*" (Goldschmidt and Tatsa,

[2] In regards to the researches on cognitive aspects in creative thinking, many researchers have analyzed protocols during sketch-based design tasks, through which design scientists have better identified the aspects of design creativity and cognitive process of designers. For extensive case studies in analyzing design activity, please refer to Cross, Christiaans, and Dorst (1996).

2005, p. 594), which have been widely accepted as a useful and innovative scheme for representing evolving design processes, as shown in Figure 5[3] which illustrates features in linkograph.

Table 3 Terminologies and features in Linkograph (Goldschmidt, 2014)

Terminology	Feature	Implication
Chunk	Graphically distinct, discernible triangular clusters of nodes	It shows a high rate of inter-connectivity between a specific range of design moves. Implying a cross-examination of relevant properties, related questions, and possible implications of a design issue
Web	Smaller than chunks, denser clusters of nodes	It shows a more intensive generation of many links among a relatively small number of moves. Webs are found when a specific clarification is needed or when an idea is being built up by bringing up several of its aspects almost concurrently.
Sawtooth	Chains of nodes	It shows that the designer is not engaged in a synthesis process but rather in a way that may not widen or deepen the investigation of the design problem.
Backlink critical moves	Design moves with many backlinks	The design move draws upon or consolidated lots of previous moves. Convergent thinking
Forelink critical moves	Design moves with many forelinks	The design move inspires many future design moves Divergent thinking

The moves represent the small steps that transform the design search. Some of the moves are then interrelated through backlinks to previous moves or forelinks to subsequent moves (Goldschmidt, 1995, p. 195). The link that connects between the moves is subsequently established when "*contents of two moves have enough in common to qualify this commonality as a link*" (Goldschmidt and Tatsa, 2005, p. 595). However, these links are conceptually very different in the sense that "*backlinks record the path that led to a move's generation, while forelinks bear evidence to its contribution to the production of further moves*" (Goldschmidt, 1995, p. 196). Moreover, Goldschmidt asserts that forelinks are manifestations of divergent thinking, and backlinks are indications of convergent thinking, as shown in Table 4. Other terminologies, i.e., 'chunk,' 'web,' 'sawtooth,' 'backlink critical moves,' and 'forelink critical moves' are further elaborated, as summarized in Table 3. Also, Goldschmidt identified that the ratio between the number of links and the number of moves is positively correlated with design creativity. In

[3] In her method, designers' protocol data, which is derived from a diverse source of origins during a design session, such as video recordings, sketches, post interviews, or discussions, is represented by a set of design moves and link nodes between moves. To make a linkograph that is composed of the sequentially listed moves and links among them, a protocol of a design session is parsed manually into a sequence of short semantic units, based on the judges' design expertise and common sense. These units are interpreted further in a linkograph. Since ideas evolve in a loop, the linkographic representation can be regarded as an effective way to trace the emergence and evolution of ideas. Consequently, a linkograph can provide a mechanism for tracing design procedures.

particular, the most significant elements in a linkograph are critical moves, which are particularly rich in links. Goldschmidt claims that a high ratio of links between design moves characterizes an effective design problem-solving process (Goldschmidt, 1996). The interconnectivity of these link nodes can provide insights into the ideation process. For example, if these nodes' density is too sparse, the process could be considered poorly structured, in which the designer is not engaged in a synthesis process, and vice versa.

Table 4 Implications of the high density of forelinks and backlinks for design thinking

Density of links	Implications
A high number of forelinks	The design move inspires lots of subsequent design moves Standing for steps forward, the consideration of more options and possible solutions, further development Manifestations of divergent thinking
A high number of backlinks	Design move drew upon or consolidated lots of previous moves Standing for appraisal, evaluation, and confirmation Gathering ideas as convergent thinking

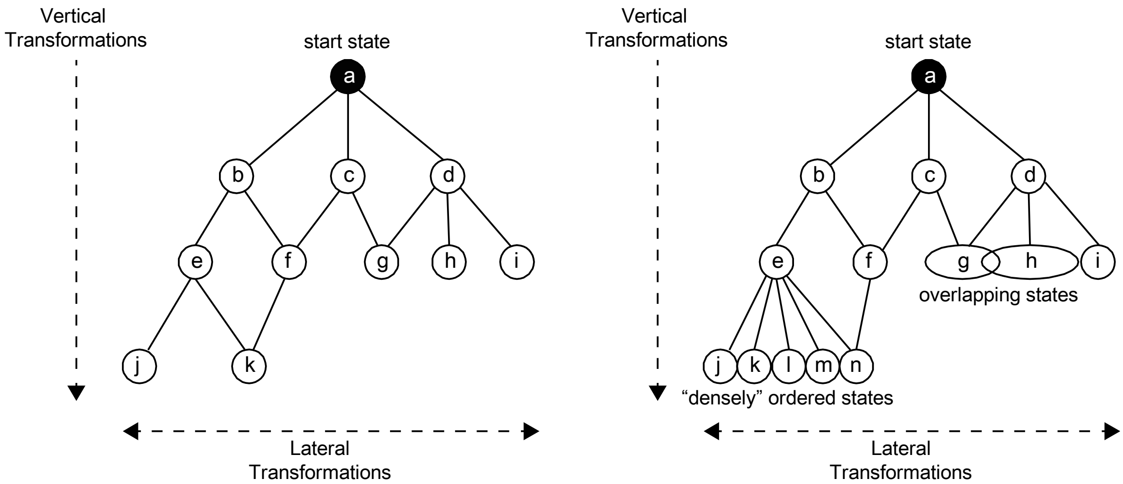

Figure 6 Concept of state-space deemed to be necessary for well-structured problems (left) and ill-structured problems (right), redrawn from Goel (2001, pp. 236–237)

In a similar context, Goel (1995) distinguished two types of discernable transformations after analyzing the progress of architecture design projects, as discussed previously in Subsection 2.1.4. He distinguished four phases in design problem solving: problem structuring, preliminary design, refinement, and detailing and notes that each phase differs in the frequency and types of transformations that designers apply. In particular, the contrasts between "preliminary design" and "refinement and detailing design" have been made; the preliminary design is a phase where ill-structured problem solving is mainly applied to facilitate the generation and exploration of creative alternatives. Shifts of focus correspond to what Goel called 'lateral transformations,' which involve exploring a variety of kernel ideas and widening the problem space. Contrastingly, continuing the sequence of related thoughts corresponds to what he calls ‘vertical transformations,’ which denote exploring a more detailed, exacting version of the same design idea, therefore, deepening the problem space. Also, he identified three properties (i.e., overlapping of states, densely ordered states, and ambiguity of states) of ill-structured representations that facilitate lateral transformations and exploration of alternative solutions (Goel, 2001, pp. 236–237), as shown in Figure 6.

Recently, it is widely accepted that creativity in design demands both convergent and divergent thinking as follows:

- Goel points out at least two different types of transformations, which are variously referred to as divergent/lateral and convergent/vertical transformations, are required “*for the widening of the problem space and the exploration and development of kernel ideas*.” (Goel, 1994, p. 70)
- Rodgers, Green, and McGown (2000, p. 461) explored Goel’s concept further and concluded that “*good design is a result of the balance between lateral and vertical transformation at these early stages rather than an extreme lateral bias. It is likely, however, that the balance will shift to an extreme (and finally total) vertical bias as the design representation progresses towards the embodiment and detailing stages.*”
- Van der Lugt (2000, 2003, 2005) had conducted several types of research on problem-solving techniques that are supposed to structure and stimulate creativity. In the study in 2003, he investigated the relationship between the creative qualities of ideas generated and the integratedness of the design process with respect to those ideas. His results show that there exists a positive relationship between the well-integratedness of ideas and those ideas' creative qualities.
- Cai, Do, and Zimring (2010) developed an extended version of the linkograph and a distance graph in order to explore the effect of inspiration sources on the design process. Based on the analysis of van der Lugt (2000)’s approach to the measurement of creativity in the design process, they conjectured that “*a well-integrated creative process should have a large network of links and a balance of link types*” (Cai, Do, and Zimring, 2010, p. 157).
- Suwa and Tversky (1997) examined what information architects think of and read off from their freehand sketches and revealed how they perceptually interact with and benefit from sketches. For this, they decomposed the entire protocol of a participant into segments and analyzed the structure of dependency links among segments, i.e., dependency chunks. Their analysis showed that “*the design process consists of smaller cycles of focus shift and continuing thoughts on related topics*.” (Suwa and Tversky, 1997, p. 401). Also, Tversky and

Chou (2011, p. 210) posit that both divergent and convergent thinking are needed to succeed in designing.

- Goldschmidt (2016) observes that both divergent and convergent thinkings in creative design are needed and advocates the claim that they occur all but contemporaneously. As discussed above, she claimed that "*forelinks are manifestations of divergent thinking and backlinks are indications of convergent thinking*" (Goldschmidt, 2016, p. 118). Her data from several empirical studies confirmed the proposition that "*a process of designing which is considered creative displays a balance between critical moves due to a high number of forelinks and critical moves due to a high number of backlinks.*" (Goldschmidt, 2016, p. 118)

In Section 2.1, the designer's approaches to problem-solving are discussed, focusing on top-down, breadth-first approaches from the prescriptive design process model, and opportunistic approaches from findings in descriptive studies. Moreover, the co-evolutionary nature of developing problem- and solution- spaces and exploration of alternative solutions during the design process are discussed.

2.2 Design Creativity and Obstacles

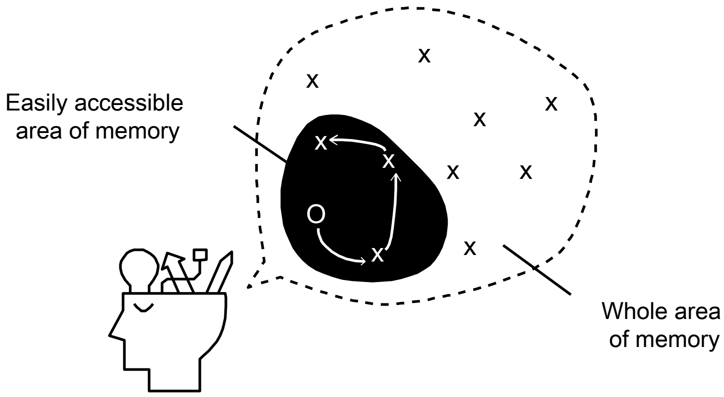

Figure 7 A cognitive model showing a search for an easily accessible area of a designer's memory

Section 2.2 discusses the design process issues, focusing on design creativity, obstacles, and approaches to overcome the obstacles through the literature review. As discussed in Subsection 2.1.2, designers explore a large quantity and variety of potential solutions before choosing the most satisfying design that is supposed to fit their requirements best. To develop a good solution base, they need to explore both a problem space and a solution space during the concept (or idea) generation stage. An interesting finding related to the quantity and variety of potential solutions is the frequency of the idea generation by a human designer is not evenly distributed, and the variety as well (Beaty and Silvia, 2012, p. 309). *How do the frequency of the idea generation and the variety of solutions change during design development?*

2.2.1 Idea Generation

Empirical studies have been conducted to answer this research question. Designers can quickly and easily search their minds at the early stage of idea generation and develop solutions using familiar ideas, as represented in Figure 7. Therefore, well-known solutions tend to be generated quickly at the beginning of problem-solving (Guilford, 1979, p. 4). After obtaining these relatively easily accessible concepts, however, they have more difficulty in developing new solutions. In order to develop relatively new ideas, it is conjectured that they must search less easily accessible areas of their memory (Howard-Jones and Murray, 2003; Snyder *et al.*, 2004; Tsenn *et al.*, 2014, p. 502) according to cognitive theories of memory search (Brown *et al.*, 1998; Nijstad and Stroebe, 2006; Rietzschel, Nijstad, and Stroebe, 2007). Moreover, the rate of idea generation decreases asymptotically over time (Howard-Jones and Murray, 2003; Snyder *et al.*, 2004; Tsenn *et al.*, 2014, p. 502), as depicted in Figure 8.

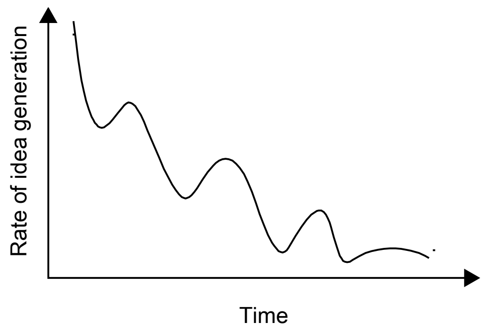

Figure 8 A general model showing how the rate of idea generation decreases asymptotically over time

Rather than developing new design ideas in parallel, designers spend more time on each solution to develop solutions based on transformations in the later design stage (Tsenn *et al.*, 2014, p. 503). Such an approach can make a difference in the quality and originality of design ideas that are developed in different design stages. For example, it is identified that solutions developed in the later design stage are more unique than those in the early design stage (Beaty and Silvia, 2012, p. 311; Christensen, Guilford, and Wilson, 1957, p. 87). However, it does not mean that the solutions that are developed earlier are not all unique and feasible. Moreover, early solutions, whether kept or not, can be characterized as references to develop more unique and feasible solutions.

Before explaining the evaluation process of outcomes, it is necessary to introduce how creativity has been measured shortly. When it comes to the evaluation of how creative each idea is, Amabile's (1983) approach is frequently adapted in design studies. For example, the variety of solutions can be measured by using other relevant metrics such as the uncommonness of design ideas and remoteness of association between ideas. Research finds that both uncommonness of ideas and the remoteness of association between ideas increase as time passes (Beaty and Silvia, 2012). For example, ideas and solutions in a later stage tend to be better than initial ones (Guilford, 1979). This kind of trend is called the "*serial order effect*" in idea generation (Beaty and Silvia, 2012, p. 309). According to the associative model of creativity pioneered by Mednick (1962), it is argued that divergent thinking denotes a process of spreading activation in semantic memory, and creative ideas come after activating and connecting distance concepts by the process (Beaty and Silvia, 2012, p. 310). This serial order effect reflects the gradual spreading of activation from close and apparent associations to remote and unusual ones. As remote associations increasingly become active and available, and the rate of solution generation slows gradually. From this perspective, it seems beneficial to support human designers in developing solutions based on transformation, which allows for saving time and activating and connecting distance concepts. However, there is an important design issue, "design fixation," which is known to affect designers' idea generation.

2.2.2 Design Fixation

When designing something new, designers are often influenced by sources of inspiration and previous solutions. In order to create a new idea, they often transform, combine, or adapt elements of various sources (Ward, 2007). Also, analogical reasoning by reusing knowledge from specific previous design projects has been observed in various cognitive studies (Ball, Ormerod, and Morley, 2004; Visser, 2009). Through this process, they use visual representations such as drawing, image, and sketch as external stimuli; however, they tend to be sensitive to them (Goldschmidt, 2001). Once starting to create a new solution idea to design problems, they often become too attached to some of the sources' features and elements, so they commonly struggle to conceive new creative solutions beyond being attached. The concept of 'design fixation' was coined to refer to '*blind adherence to a set of ideas or concepts limiting the output of conceptual design*' (Jansson and Smith, 1991, p. 3). *How does the design fixation appear and influence problem-solving?* Fixation can occur unconsciously; therefore, it seems to be challenging to diagnose whether a human designer is fixated or not. While designing, designers can be unconsciously fixated on a familiar idea or the ideas they think of first. Fixation affects how humans generate novel ideas and designs (Jansson and Smith, 1991; Smith, 2003). Design fixation during idea generation is, in many cases, admitted undesirable. To be more specific, design fixation during idea generation can hamper designers from developing feasible design concepts by "*anchoring a designer's creative thoughts and actions in the past at the stage of design when creative thinking and actions may have their greatest impact*" (Youmans and Arciszewski, 2014, p. 129). 'Design fixation' has often been used in a narrower sense. It is used to refer to an over-reliance on the features of the pre-existing design (Purcell and Gero, 1996) or to a tendency to structure new solution creations that conform to a familiar model (Finke, 1996). A number of cognitive studies acknowledged that fixation impedes design creativity. For instance, when a design instruction is accompanied by a pictorial example, individuals tend to generate fewer and less novel designs, which conform to the example (Jansson and Smith, 1991). Furthermore, during a brainstorming experiment, it is identified that individuals generate fewer unique ideas when they are exposed to another's ideas (Kohn and Smith, 2011). The generated ideas are more likely to conform to ideas to which they were exposed, and the rate of conformity increased to the extent that is in proportion to the number of exposed ideas (Kohn and Smith, 2011). Ironically, however, design fixation is not entirely admitted as a negative aspect to design activity. If designers are fixated on some aspect of the design solutions and utilize the moment for an in-depth exploration of a narrow set of viable solutions, it might contribute to time-saving, which leads to the cost reduction of a design project (Bilalić, McLeod, and Gobet, 2008).

Nevertheless, if they are fixated at the conceptual design stage when diverse ideas are needed to be tested, their creative activity can be impeded by keeping on generating designs that are similar to the previous example (Purcell and Gero, 1996; Smith, 2003; Smith and Blankenship, 1991). Therefore, I will consider that design fixation has a negative influence on design creativity, particularly in the conceptual design process. Also, a number of studies suggest that fixation impedes both divergent thinking and convergent thinking, which are admitted as two principal forms of creativity (Smith, Ward, and Schumacher, 1993). Whereas the generation of multiple ideas in diverse directions stands for divergent thinking, searching for the unique or best solution to a specific problem stands for convergent thinking (Cross, 1985, p. 158; Lu, Akinola, and Mason, 2017). Both of these are considered the main underlying principle in creative problem-solving in order to generate creative yet good design solutions (Lu, Akinola, and Mason, 2017, p. 64). In the conceptual design stage[4], relatively more diverse ideas are suggested through divergent thinking. In particular, four guidelines (Treffinger, Isaksen, and Stead-Dorval, 2006, pp. 8–9) for brainstorming are well-known to help divergent thinking: 1) deferring judgment, which indicates postponing judgment until a full range of options is generated; 2) striving for quantity, which indicates trying to generate the greater number of options because it may increase the possibility of discovering options which are original and useful; 3) Freewheeling and accepting all options, which indicates trying to discover the value of all options that come to mind; and 4) seeking combinations, which indicates trying to look for ways to connect options and build novel and useful ones. In the middle stage, both divergent thinking and convergent

[4] Design processes are commonly represented as models composed of many distinctive stages, e.g., task clarification, conceptual design, embodiment design, and detail design in Pahl *et al.* (2007). During the conceptual design phase, several concepts representing a set of physical principles for solving the problem are generated. These concepts are transformed into a more concrete representation that allows assessment and comparison, e.g., Wynn and Clarkson (2005).

thinking suggest multiple ideas while achieving the chosen idea's specific characteristics. Through convergent thinking, the options are screened and evaluated. Furthermore, convergent thinking may be dominant at the very last stage before a final choice has to be made. Many questions remain regarding how to manage both convergent and divergent thinking effectively across the design process.

2.2.3 External Representation, Memory and Sunk Cost Effect

Designers may develop one idea/concept and then develop this into another during the conceptual design phases. Throughout this process, external representations are indispensable in facilitating new ideas and design concepts and elaborating new ideas and concepts (Do *et al.*, 2000; Goel, 1995; Goldschmidt and Tatsa, 2005; Suwa and Tversky, 1997). *How does the externality of representation help facilitate the generation of new ideas and design concepts?* First of all, external representations allow easier access to earlier design ideas, which is likely to stimulate increased use of them (Akin, 1986). In other words, they can facilitate the re-use of previously generated design ideas and connect links between ideas. Also, external representations are known to "*reduce working memory load by providing external tokens for the elements, which must otherwise be kept in mind"* (Suwa and Tversky, 2002, p. 341). Rather than both keeping elements in mind and operating on them, external representations free working memory to perform mental calculations on the elements (Newell and Simon, 1972; Tversky, 2001). Scaife and Rogers (1996) used the term "*Computational offloading*" in general in order to describe how differential external representations can reduce the mental effort involved in achieving a task. Also, designers can use external representations as "*visuospatial retrieval cues for their long-term memory*" (Suwa and Tversky, 2002). Moreover, discovery and inference are easily made from external representations by allowing perceptual judgments about the size, distance, and direction. Memory retrieval is a critical part of concept generation as designers must build ideas that they already know (Nijstad and Stroebe, 2006). In an experiment on the impact of working memory on idea development by expert architects, Bilda and Gero (2007) showed that working memory limitation impacts the linking of ideas. External representations, such as sketching, help reduce the cognitive load of the design process.

Another factor that has a significant influence on the course of a designer's action, which is related to the design fixation, seems to be related to the effect of sunk cost. The "sunk cost effect" refers to "*a greater tendency to continue an endeavor once an investment in money, effort or the time has been made*" (Arkes and Blumer, 1985, p. 124). When designers solve complicated design problems, it is commonly observed that they spend a considerable amount of time and effort, such as drawing sketches, building physical prototypes, and communicating ideas with other stakeholders. If the sunk cost that a designer spends is exceedingly high, it makes one hesitate to choose another idea that is drastically different from the current idea. It can lead to higher design fixation, which can influence a person's decisions. This theory explains that "*if the cost sunk into a course of action is high, a person is more likely to stick to that course even if it is more logical to choose a different course of action*" (Viswanathan and Linsey, 2012). Reversely, if the sunk cost is low, I guess it might be relatively more manageable for a designer to generate drastically different ideas, leading to lower design fixation. Designers' tendency not to pursue the search for multiple solution alternatives may be ascribed to the sunk cost. It provides a substantial implication when developing a design support methodology.

Other reasons that designers may strategically avoid generating and exploring multiple solution alternatives include: (1) lack of motivation in order to seek better solutions when congenial and satisfactory solutions are found, (2) time pressure that they experience, and (3) limited conceptual knowledge that they have relating to the particular problem at hand.

2.2.4 Approaches to Support Design Creativity

Various forms of methods have been known to help reduce the design fixation during the idea generation. A few well-known methods that have been developed with the aim of promoting and maximizing the generation of ideas include taking short breaks from the task (Smith and Linsey, 2011), using physical material to prototype (Youmans, 2011b), or incorporating formal design heuristics (Yilmaz and Seifert, 2011), sharing ideas in groups (Youmans, 2011b), and task-switching (Lu, Akinola, and Mason, 2017), which can provide insight for improving design support methods.

There are some cases in which insightful ideas or solutions about difficult problems are realized after having a short break (Nijstad and Stroebe, 2006; Paulus *et al.*, 2002; Youmans, 2011a). The short break, which is called 'incubation,' is defined as the stage of the creative process after the initial efforts to solve a problem have paused (Smith and Linsey, 2011; Tsenn *et al.*, 2014). During the incubation period, a designer stops consciously working on the design problem for a certain duration. Such a cognitive pause would allow the designer to put the previous set of solutions behind him or her (Smith and Blankenship, 1991) and leave the designer "*free to take a fresh look at his or her problem*" (Woodworth and Schlosberg, 1954, p. 841). It is known that including the incubation period in the concept generation process is, in some cases, effective in the reduction of fixation (Kohn and Smith, 2011). The incubation period seems to be related to the "*serial order effect*," which is defined as the "*tendency for later responses to a divergent thinking task to be better than earlier ones*" (Beaty and Silvia, 2012, p. 309). As discussed in Subsection 2.2.1, the serial order effect can explain why designers tend to develop quite unique and creative solutions in a later design session. This statement is supported by Christensen et al.

(1957) and Parnes (1961). From several divergent-thinking tests, Christensen *et al.* (1957) discovered both uncommonness (originality and novelness) of ideas and remoteness of associations tend to increase as time passes in the working period. Similarly, Parnes (1961) noticed that students in problem-solving classes produce both useful and unique ideas later on in the session, which is evidence of the serial order effect. According to the findings of Guilford (1979) and Parnes (1961), solutions with unoriginal and conventional ideas are generated quickly in the early session. In contrast, ones with high quality and originality involve transformations (i.e., modification, shift, or transition of existing ideas), requiring more time and effort to conduct. In short, their experiments on the effect of having a short break during idea generation prove that the incubation period can be effective in avoiding design fixation.

Also, there have been a few studies on the effect of the physical prototype in idea generation (Cai, Do, and Zimring, 2010; Deininger *et al.*, 2017; Youmans, 2011b). A physical prototype is commonly used to generate the idea in most design areas. Viswanathan and Linsey's (2012) experiment on the effects of physical models as a tool for idea generation indicates that the use of physical models is advantageous to correct the flaws in a designers' mental models. Physical models can be used to increase the probability of functional idea creation. Additional supporting research on the advantage of the use of physical prototyping shows that individuals who develop tools in an environment that facilitates physical interaction and prototyping create more innovative and better-performing tools (Youmans, 2011b).

According to the analysis of sequences of exploratory concept sketches by an expert industrial designer working on a real-world project, it appears that design heuristics seems to promote variation in concepts and transform existing solutions (Yilmaz and Seifert, 2011, p. 384). The research supports the claim that incorporating the use of design heuristics can contribute to maximizing creativity and diversity in design at the expert level. Furthermore, the design heuristics allows designers to generate more various candidate concepts to consider in the early design stages by providing 'cognitive shortcuts' (Yilmaz *et al.*, 2016).

Sharing ideas in groups affects design fixation. Fixation can ostensibly be avoided or reduced by sharing ideas in groups of designers instead of working individually (Youmans, 2011b). In a study on the influence of interactions between designers on creativity-relevant cognitive processes, it was found that stimulating the cognitive process of memory retrieval exists and shared design entities in the collaborative setting play an important role in stimulating memory retrieval (Sauder and Jin, 2013). It can be assumed that interaction among individuals in a group setting facilitates the interchange of ideas, fostering mutual fertilization. On the contrary, in a series of experiments on the effects of others' ideas on brainstorming, it is observed that people conform to ideas to which they were exposed, and the rate of conformity increased as the number of ideas exposed increased (Kohn and Smith, 2011). Arguably, this evidence shows that fixation effects can occur while sharing ideas in groups, depending on how ideas are shared.

The task-switching approach can elevate the designers' creative performance. Theoretically, it can be argued that switching between creative tasks can allow designers to set the tasks aside, which may alleviate their cognitive fixation on ineffective ideas (Lu, Akinola, and Mason, 2017). This strategy enables individuals to solve the focal task with a fresh mind, thereby improving their creative performance (Sio and Ormerod, 2009).

So far, various aspects of designers' problem-solving and obstacles to design-creativity are discussed. What is identified is that any methods that allow people to approach problems with fresh eyes may evidently improve creative performance. The effects of fixation can be mitigated through having a short break, working with prototypes and design heuristics, sharing ideas in groups, and task-switching. *How can design support unburden a designer's cognitive overload and stimulate new design ideas and concepts? How can the design support reduce the mental effort involved in achieving a task?*

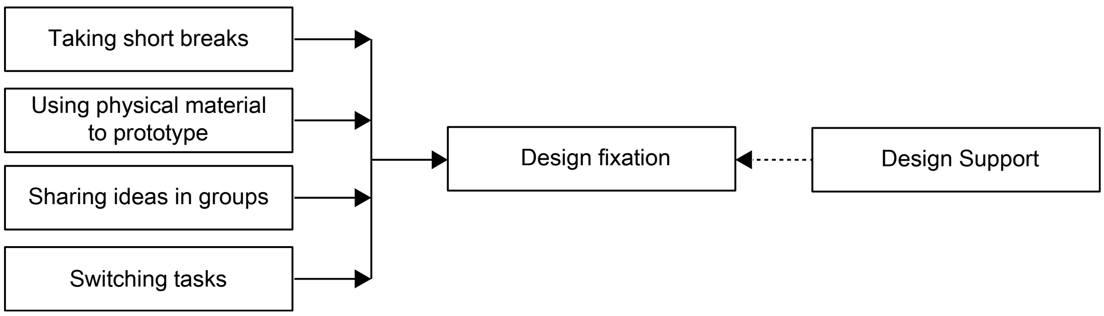

Figure 9 Preventives of design fixation

The preventives of design fixation in Figure 9 provide important practical implications because creativity is vital to design problem-solving. In the off-the-shelf CAD software products, I think that the optimal situation may be when designers choose to switch tasks and mitigate the mental overload spent on managing the overwhelming design information. This idea can be realized by providing them a more interactive explorative capacity. If they have reached a dead-end in terms of design problem solving, they can switch as a way of refreshing themselves, which allows incubation to occur potentially. Through the design support, designers get assisted to keep their focus of attention high and prevent themselves from becoming cognitively exhausted, which enables them to be more creative on the design tasks. In Section 2.2, important aspects concerning design creativity and its obstacles are discussed, focusing on human designers' idea generation, design fixation and related issues, and approaches used to support design creativity. Section 2.3 will discuss the design object, i.e., urban design.

2.3 Thinking about and for Urban Design

This session discusses the most relevant aspects of urban design regarding the research topic. The literature on prescriptive methodology in urban design abounds, but the empirical studies on design thinking have relatively received little attention in urban design. I will provide the theoretical background of urban design as problem-solving and decision-making. There is always a risk that computer-aided procedures can substitute mindless algorithms for creative thinking. Instead, this session will focus on how to help designers increase more creativity in their work by supporting a range of aspects during the design process.

2.3.1 Relating Parts to a Larger Whole in Urban Design

What is urban design? Urban design, which is used in a narrow sense in this dissertation, involves manipulating and structuring a decision environment that enables others to author the built environment (George, 1997, p. 148). The decision environment is to realize an intended state of the built environments, but without actually designing the components of the environment (George, 1997, p. 148). Urban design is a process that consists of analysis and synthesis (Lawson, 2006). The desired state of urban space is achieved by relating 'urban *parts* (e.g., individual actions, buildings or building designs) to a larger *whole* (e.g., urban form)' (Tiesdell and Macfarlane, 2007, p. 407); therefore, urban design involves the shaping of spatial configuration. Popularly, masterplans as a form- and site-based development control tool are often used to guide and control land and property development. Of course, depending on the spatial scale, qualities and features, the term 'masterplan' is used more generally to encompass a broad range of concepts, such as 'spatial strategies,' 'development frameworks,' 'masterplans' and 'design briefs' (Tiesdell and Macfarlane, 2007, p. 408).

In most masterplans, a set of rules about the desired urban/built form is provided to consider ideas about the desired urban form and the relationship between the urban 'parts.' In this process of relating 'parts' to the larger whole, it is expected that urban designers try to reuse knowledge. In the field of urban design, patterns, types, heuristics, classification, and expertise, which are slightly different in their meaning, seem to be used interchangeably. Among these, patterns[5] that often refer to a specific geometric layout may be used comprehensively. Designers may take a

[5] Since the contribution of Alexander, Ishikawa, and Silverstein (1977)'s pattern languages, there are substantial signs of progress in the use of patterns. The original aim of the book is to support architects in creating well-designed buildings and landscapes. The idea of pattern languages is a collection of connected examples describing successful design solutions that correspond to problems that frequently recur in specific contexts. A solution that a pattern describes for a particular problem is typically represented abstractly, with the intention of enabling designers to solve concrete instances of the conceptual problem.

specific pattern to use a broad range of useful guidance from past solutions and apply it to solve their design problems in a refined form.

The term "*bounded rationality*," which Simon (1957) coined, can provide a theoretical justification for design patterns' utility. In short, "bounded rationality" indicates the idea that rationality is limited when individuals make decisions. This is due to the cognitive limitations of the human mind, the time available to make a decision, and the intractability of the problem. Individuals are not consistently rational in their thinking. From this perspective, designers always tend to consider a small part of the design information in the real world. Patterns are mostly represented by containing a small part of the design information in a specific context. It is enabled through abstraction or disambiguation by removing details from an intricate design context and keeping a set of necessary design features (Simon, 1973). If designers use patterns in a particular design context, it is more efficient to control the available information in a manageable manner for a design process and decision-making within this design process. Moreover, the patterns have been used in order to develop formal algorithms to generate urban designs (Beirão *et al.*, 2012).

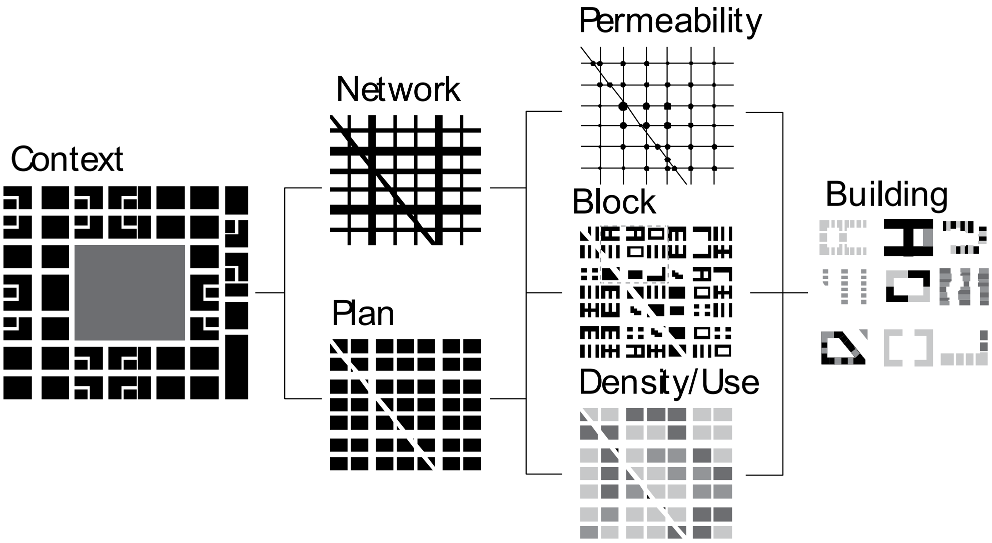

Figure 10 Urban patterns

Patterns evolve over time and increase in their size since new knowledge in urban design is constantly created. A few classification systems for patterns in urban design have been proposed[6]. However, recently, the most rigorous study of urban patterns, which is most relevant to this research, was presented in a book, "*Streets and Pattern*" (Marshall, 2005). His book focuses on the analysis of street networks and their structuring, but it is limited in that he does not deal with broader entities for the urban form such as blocks (or quarters) and buildings. Most recently,

[6] For a brief review of a typological classification system in urban design, see: Adam and Jamieson (2017).

Adam and Jamieson (2014) developed a typological method for the comparisons of masterplans to quantitatively analyze the trends of the known contemporary masterplan and typological classification system, which is adapted for defining urban entities in this study, as shown in Figure 10. Urban design patterns can describe a comprehensive characteristic across a range of scales, from the city scale down to the building scale, as shown in Table 5.

Table 5 Urban pattern: category and constituent cases (Adapted from Adam and Jamieson, 2014)

Category	Constituent Cases	Description
Context	Contained/Extension/Greenfield/Infill	The relationship between the masterplan and its surroundings
Plan Type	Orthogonal/Radial/Clashing/Distorted Grid/Grid with Diagonals/Townscape (Organic)/Unbounded/Olmstedian Urban/Suburban/Stem Pattern/Multiple Plan Type	The overarching layout of a masterplan – how blocks are arranged to create a network
Network Articulation	Street Pattern/Central axis/feature/Boulevard/Avenue	The proportion, scale, and layout of streets and roads
Permeability	Intersections per Area Connectedness	The degree to which the masterplan provides a choice of routes and pathways, making the place accessible
Density	Height/Built Form per Area	A broad understanding of the built-form's density
Use	Residential/Mixed Use/Zoned	A functional mix of the masterplan
Block Type	Irregular/Rectilinear/Curved /Partially closed/Perimeter/Super/Circular Block	The overarching layout of a block – how buildings are arranged to create spaces: private or public, pedestrian through-routes, or used for parking, etc.
Building Articulation	Row/Detached//Solitaire/Ribbon	More details of formal characteristics in buildings and plots in a block

When an architect designs a building, he or she concerns about its surroundings. Analogically speaking, urban designers take into consideration issues when relating the masterplan to its surrounding. The *context* is used to describe the relationship between the masterplan and her surroundings. It can be differentiated depending on whether the masterplan is 1) located within an existing settlement or 2) added onto an existing settlement, 3) without any physical relationships with existing settlements, 4) made up of individual buildings or blocks within existing settlements. The acceptance of contextual information is critical because the patterns of an existing settlement can influence the masterplan's patterns. The *plan type* is used to describe the overarching layout of a masterplan, showing how blocks are arranged to create a network. Previously existing features, such as topography and cultural heritages, can influence the selection of the plan type, and sometimes, more than one plan type can be mixed in a single masterplan. The selection of a particular plan type is strongly related to the traffic flow and pedestrian movement. *Permeability*, which denotes the degree of the place accessibility to which the masterplan provides a choice of routes and pathways, can be conveniently measured by identifying the average number of interactions across a masterplan and their distribution. It is evaluated by measuring the average distance between intersections and, in addition, a maximum and minimum distance between intersections. *Block types* describe the overarching layout of a block. It displays the arrangement of buildings and spaces in a block. Besides, the *network articulation* describes the proportion, scale, and layout of streets and roads, which surround incident blocks. More than anything else, block types and network articulation help envision the district community's neighborhood activities. The *land use* of blocks (or a district) is used to understand the functional mix of a masterplan. The permitted maximum height of a building, the building coverage, and the floor area ratio are used to control a built area's density. At the finest level, *building articulation* describes more detailed characteristics of a masterplan. For a masterplan, the layout of the building footprint and, at best, the building roofs' shape are defined by considering the corresponding zone ordinance and its surroundings.

In short, it is identified that urban designers commonly use patterns for relating urban parts to a larger whole. The patterns which are featured as absolute positions and lengths can describe a spatial form, which is composed of various elementary building blocks, and they can be used as a reference for future urban design. Archetype urban patterns such as gridiron, hexagonal, radial, iron-grind, and other kinds of patterns, either they may be designed or emerged, are often used in urban design books (Marshall, 2005).

2.3.2 Issues and Process in Urban Design

Not only to identify the design method practiced by urban designers, but it is also necessary to analyze what kinds of issues are their concerns and how they are achieved. In this Subsection, I will identify urban design issues and processes based on the literature review. However, it is not intended to restrict or circumscribe the bounds of urban design issues. Instead, I will try to leave it open and highlight the co-evolutionary nature of problem-solving in urban design, which is a continuation of the discussion in Subsection 2.1.2. The process of designing urban places includes knowledge spanning the social, cultural, economic, and physical dimensions. For example, as a method to assess the objectives for urban renewal projects, criteria and their corresponding indicators were proposed, as shown in Table 6. It is common that there exist problems that urban designers confront in practice that cannot be clearly defined (Biddulph, 2012, p. 12). Designers must also pay attention to the objectives (such as traffic flow, building regulation, measures of density, permeability, and integrity) and subjective, interpretive, and political. It is not odd that they try to come up with an urban design that is creative and original, and they might be eager to design settlements that are, for example, either delightful and even shocking. A probability that specific rules given might be broken exists, and the design solution is only one part of an ongoing evolution about the settlement to which it has been applied (Biddulph, 2012). Urban design proceeds not by the discrete steps from analysis to the final design, either linear or circular leading to a single solution. However, its process is cyclical with iterations, which repeat the recursive feedback loops. This is because designers deal with ill-defined requirements and wicked problems (Buchanan, 1992; McCall and Burge, 2016; Rittel and Webber, 1973), act under conditions of bounded rationality, and thus accept satisficing solutions (Simon, 1955).

Table 6 Objectives, criteria and indicators for urban renewals (Lee and Chan, 2008a; 2008b)

Objectives	Criteria	Indicators
Economical Sustainability	Access to public facilities	Public facilities within 500m of accommodation
		Ease of access to public facilities
	Green design	Incorporation of passive design
		Quality of passive design
	Provisions for the establishment of different businesses	Types of business premises
		Quality of shops and services
	Community involvement	Form of involvement
		Degree of participation
	Compatibility with a neighborhood	Harmonious environment
		Impact of development
	Convenience, efficiency & safety of pedestrian & public transport users	Frequent means of travel (except for work)
		Quality of pedestrian walkways and public transport facilities
Environmental Sustainability	Access to work	Work traveling habits
		Average journey time for the citizens to get to work
	The sense of community	Social cohesion
		Citizens' satisfaction with the local community
	Green design	Incorporation of passive design
		Quality of passive design
	Building form	The density of development within the renewal site
		Quality of building development
	Provisions of open spaces	Percentage of open spaces being provided
		Quality of open spaces
	Rehabilitation of repairable properties	Percentage of existing properties being retained
		Degree of rehabilitation
Social Sustainability	Provisions for disabled, elderly/children	Types of provisions for disabled, elderly & children
		Adequacy of accessible design and special facilities
	Green construction	Incorporation of environment-friendly practices
		Quality of environment-friendly practices
	Conservation of local distinctiveness	Appreciation of local characters
		The uniqueness of the renewed area
	Availability of local employment	Number of jobs created per 1,000 ㎡
		Quality of jobs created
	The adaptability of development to the changing needs	Capability to cope with future changes
		Degree of adaptability
	Access to open space	Average walking distance to the nearest open space
		Ease of access to open spaces

Therefore, the overall process in which the design problem and solution co-evolve is explorative in nature (Dorst and Cross, 2001). From this viewpoint, when an overall design form is satisficing, the iteration terminates, and the design task is accomplished. The design process models that reflect the iterations are ubiquitous in the classical design process literature. For example, Hillier, Musgrove, and Sullivan (1972) described the design process as a cycle of ‘conjecture’ that produces “proto-models” of forms, producing intangible beliefs. The proto-models are evolved through the test or evaluation of the beliefs. Based on the model of Hillier *et al.* (1972), March (1976) proposed, so-called ‘Production-Deduction-Induction model’ of the rational design process. Later, Zeisel (2006) described a built environment's design process as a spiral, as shown in Figure 11.

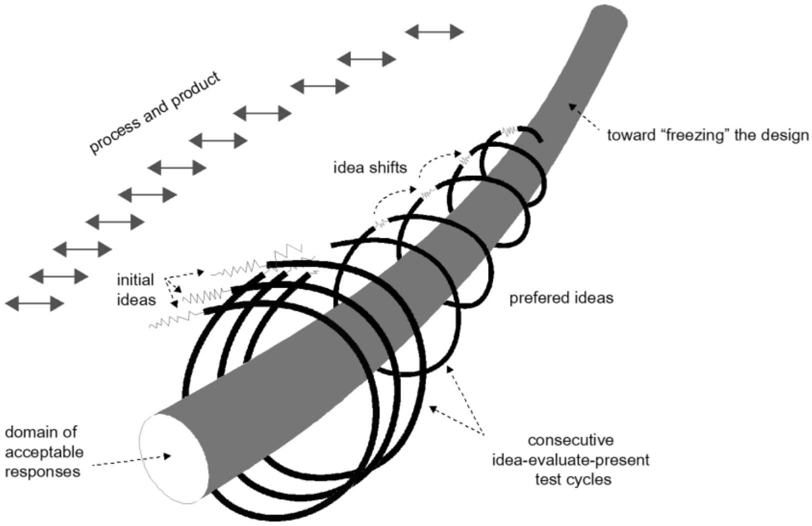

Figure 11 Zeisel’s design process model of the built environment (Zeisel, 2006)

Cross argued that much of the basic logic of urban design thinking is essentially the form of ‘abduction’ (Cross, 2006, p. 11). Dorst (2011) clarified the basic reasoning patterns, i.e., Deduction, Induction, Abduction-I (normal abduction) and Abduction-II (design abduction), in problem-solving by “*comparing different settings of the knowns and unknowns in the equation*,” as shown in Figure 12. The equation is composed of ‘what,’ ‘how,’ and ‘outcome’: the ‘what’ refers to the things (object, system, and service) in a problem situation, and the ‘how’ refers to the ‘working principle’ or the laws and methods of ‘what,’ and the ‘outcome’ refers to the results (e.g., a need to be addressed, or a value to be attained) of ‘what’ and ‘how’ through the particular reasoning process (Dorst, 2011). In the sciences, inductive reasoning informs ‘discovery,’ while deductive reasoning informs ‘justification,’ which helps us explain and predict results (or phenomena). On the contrary, abduction is defined as a mode of logical reasoning based on the “*formation or adaption of a plausible but unproven explanation for an observed phenomenon; a working hypothesis derived from limited evidence and informed conjecture.*” (OED, 2019) Rather than informing ‘discovery’ or ‘justification,’ abductive reasonings informs the “creation of value," which requires the creation of new 'what,' together with the 'how,' the working principle that helps achieve the value aimed.

Yet, there is a difference between Abduction-I and Abduction-II. Abduction-I is to create a design that operates with a known working principle and a set scenario of value creation. In Abduction-II, on the other hand, the 'how' is also unknown, and the desired value that designers wish to achieve is also somewhat indistinctive. For example, through the study on the relationship between "density and functional mix" and "travel behavior," it is possible to deduce the design knowledge that the density and functional mix are related to the reduction of travel distances, which is considered as the primary design issues for the economic and environmental sustainability in most urban design projects. However, when designers assumably try to figure out 'what' to create in order to achieve the desired value for the design objective, there is no certainty of 'how' it can be accomplished.

Equation:	What (thing)	+	How (working principle)	leads to	Result / Value (observed/aspired)		
Induction:	What	+	???	leads to	Result (observed)	→	Discovery
Deduction:	What	+	How	leads to	???	→	Justification
Abduction-I:	???	+	How	leads to	Value (aspired)	→	Engineering
Abduction-II:	???	+	???	leads to	Value (aspired)	→	Design

Figure 12 Four types of reasoning in problem-solving (Dorst, 2011, pp. 522–525)

Under this condition, individuals can be seen to randomly generate ideas for both the 'what' and the 'how,' then come up with a matching pair that does lead to the aspired value (Dorst, 2011, p. 524). Even if individuals figure out a matching pair of 'what' and 'how' which can reach the desired value, they still may doubt if there are better pairs of 'what' and 'how.' Then another cycle of proposing and testing 'what' and 'how' is practiced, which is a backward problem-solving strategy that requires thinking from the vague desired 'outcome' back to 'what' and 'how.' Dorst (2011, p. 524) called the application of a certain working principle for the creation of specific value as '*framing*,' which is the key element of Abduction-II. Dorst argued that "*starting from the only 'known' in the equation, the value that needs to be created, and then adopt or develop up a frame*" is the most logical method to approach this complex problem situation, and the design thinking contains "*a mix of different kinds of thinking*," i.e., Deduction and Induction for analysis, and Abduction-I for problem-solving. (Dorst, 2011, p. 525)

Moreover, the complexity of this kind of backward reasoning in design practices increases when there is a growth in the number of unknown 'what' and 'how' in the relatively early phase of the urban design process. In such a circumstance, designers' designerly way of knowing and thinking is the most important. Human designers' problem-solving and decision-making rely on their actual cognitive activities such as doubting, testing out, and reflecting, which are based on their a priori knowledge or previous experience and through the exploration of different combinations of 'what' and 'how.'

2.4 Urban Design Support Methods

While urban design problems that may be categorized as routine can be solved with fully or semi-automated design procedures, but those that may be categorized as creative remain elusive. As Krish (2011, p. 88) argued, the main reason is due to the complexities that are "*attributed to the multiplicity of design objectives, the contradictory and unquantifiable nature of some of these objectives, the lack of complete domain knowledge and the vastness of design space*." The main advantages of adopting generative design methods in urban design are to use computational capabilities to support human designers and (or) automate parts of the design process. Not only for achieving efficiency (multiple design instances), cost reduction, optimization, accuracy, and consistency, the generative design methods enable the exploration of larger design space and support design generation (Singh and Gu, 2012). In this Section, the most relevant, widely cited works in district, city, or urban design generation are discussed in the context of urban design.

2.4.1 Generative Design Exploration Methods

As reviewed in Singh and Gu (2012), five commonly used generative models such as shape grammars, L-systems, cellular automata, agent-based modelings (or swarm intelligence), and genetic algorithms have been known to be applied to facilitate the process of design exploration in architecture and urban design. I will briefly explain the definition and characteristics of the five generative methods as follows:

- A shape grammar is a set of shape (language) rules that can be applied in a step-by-step way to generate a set or language of designs (Knight, 2003, p. 127; Stiny, 1980, p. 347). Designs are generated by applying the shape rules, which themselves are the descriptions of the generated designs. Not only can shape grammars be used as design tools to generate design languages, but also as analysis tools to understand and evaluate existing design structures (Knight, 2003, p. 132).
- L-systems are the generative models with "*a set of production rules applied recursively through string rewriting mechanism* (Singh and Gu, 2012, p. 188)" In an application of L-

systems for design generation, the representation of the design is generated by applying various string rewriting mechanisms to design components that are symbolized as strings. The generated symbols are subsequently mapped into forms to visualize and evaluate the generated design (Parish and Müller, 2001, p. 302).

- Cellular automata are generative models with a collection of cells on a larger grid in a bounded area (Wolfram, 2002). The cells evolve according to a set of rules driven by local communication between neighboring cells (Herr and Kvan, 2007, p. 62). As the states of the neighboring cells and design constraints direct the generative process; therefore, cellular automata are context-sensitive and often complex and difficult to predict in advance.
- Agent-based modelings are simulation models with agents "*situated in some environment, that is capable of flexible, autonomous actions in order to meet its design objectives* (Jennings, Sycara, and Wooldridge, 1998, p. 8)." The agents' behavior, which has an appropriate rationale for every step it executes, can be driven by proactivity and cooperation among agents or reactivity to changes in the environment (Bonabeau, 2002, p. 7280). Therefore, unexpected results can be produced from the discrete interactions of agent-based models.
- Genetic algorithms are evolutionary models, inspired by natural evolutionary processes, with evolutionary operators (i.e., selection, crossover, and mutation) that are applied "*on a population of states in a search space to find those states that optimize a fitness function* (Gero and Kazakov, 2001, p. 71)." The quality of design solutions by genetic algorithms' evolutionary processes tends to increase with each generation (Gero and Kazakov, 1998). Therefore, genetic algorithms have mainly been used for finding optimal solutions.

Each method has been used for specific urban design purposes. For example, hierarchical top-down processes such as shape grammars (Beirão, 2012; Beirão *et al.*, 2012; Duarte and Beirão, 2011; Gong *et al.*, 2018; Mandić and Tepavčević, 2015; Stiny, 1980) and L-systems (Lindenmayer, 1968; Parish and Müller, 2001; Vanegas *et al.*, 2012) have been used to generate block layout, city road and networks, and plot subdivisions. On the contrary, bottom-up processes such as cellular automata (Herr and Kvan, 2007; Neumann, 1951) and agent-based modelings (Bonabeau, 2002; Chen, 2012; Yi and Malkawi, 2012) have been used to generate context-sensitive urban design and planning/zoning.

2.4.2 Limitation of Generative Design Exploration Methods

Based on the investigation of Singh and Gu (2012), Table 7 compares these five generative methods for urban design purpose by 'components' to define and implement the model, 'rule application,' 'main advantage' and 'limitations' of the model in terms of generative design, 'design purpose,' 'design approaches,' 'design problems,' 'design outcome characteristics,' and level of 'user intervention.' Design outcomes from the application of shape grammars and L-systems are highly repetitive and require evaluation by users. Furthermore, high user interventions are needed for the analysis of design outcomes. In the case of the application of cellular automata, the design outcome is somewhat restricted to the cells' geometry (e.g.., grid-based). Moreover, user interventions are low once cell dimension, state rules, and initial rules are defined. Though agent-based modelings are suitable for testing the usability of the design environment, such as way-finding and social/behavioral patterns, they are rarely used for geometric designs.

Generative design methods have been used in various ways for innovative design exploration. However, existing generative design methods tend to "*constrain the exploration opportunities to the design generation path, offered by the specific technique*," therefore, "*lack flexibility in supporting reflective practice* (Singh and Gu, 2012, p. 199)." The critical need identified with the generative design models is the interactivity that provides designers with the ability to control and manage the design process to achieve the desired design solutions. Moreover, many of these models have shown only limited success in supporting conceptual designing since conceptual designing's most distinguishing features are ignored. Not all requirements are known at the outset of a design process, and conceptual designing involves finding requirements and modifying them again (Cross, 2001, p. 81), as explained in Sections 2.2 and 2.3.

2.4.3 Generative Urban Design Support Methods

This Subsection discusses current urban design support methods using the different generative design generation methods. Duarte *et al.*'s model (2012b), which is called the City Induction model or the *CItyMaker* (Beirão, 2012), generates urban form by combining design patterns at the city scale. The *CItyMaker* is composed of three sub-modules, i.e., formulation module, generation module, and evaluation module. The formulation module has the role of formulating urban programs from the analysis and interpretation of the given context, which is based on Alexander's *Pattern Language* (Alexander, Ishikawa, and Silverstein, 1977). The composition of an urban solution for neighborhoods that match the program is generated in the generation module, based on Stiny's shape and description grammars (Stiny, 1980, 1981). The evaluation module is used to analyze, compare, and rank alternative solutions to meet the design's goal.

Koenig's model generates and simulates urban structures at the district scale (Koenig, 2011). Being supported by multi-agent systems and cellular automata, his model is composed of four basic levels (steps): the information level, the site development level, the building level, and the optimization level. The information level is a dynamic database for storing and retrieving local information, which includes geographic, environmental, social, and economic models of the intervention site on a large scale. The site development level generates the road networks based on six basic urban field types, i.e., a point type, a stochastic field type, a passive linear type, an active linear type, an interactive field type, and a deterministic field type, as described in Humpert (1997). Three-dimensional building volumes are extruded from the two-dimensional building footprints using cellular automata (Neumann, 1951). At the optimization level, a genetic algorithm is used to optimize the generated forms.

Knecht and Koenig's model (2012) generates plots and buildings with a given road network. More specifically, building areas are automatically allocated using subdivision algorithms, i.e., subdivided into plots of land, and can then be built based on various urban design types. The subdivision of building areas and the generation of building structures are subject to specific urban design restrictions, specifications, and parameters.

Later, this model is advanced to Koenig *et al.* 's model (2017) and Miao *et al.* 's model (2018) that can quickly generate conceptual urban design prototypes by synthesizing spatial configurations for street networks, parcels, and building volumes based on given requirements by the urban designer. In order to support compatibility with other design support models, it is implemented as a plug-in for Grasshopper/Rhino3D user interface, i.e., *DecodingSpaces* (Koenig *et al.*, 2017), which enables the user to explore many possible solutions quickly.

Luca's model (2007) uses Agent-Based Modeling and cellular automata to generate an urban form from district design up to urban and regional design on multiple scales. It is conjectured that his model seems to execute two steps, i.e., one for collecting data and the other for generating the form. The data collection step has multiple tasks coupled with existing urban and regional datasets, and the tasks integrate generative procedures in a hierarchical structure. As his model focuses on the generation in the district or a somewhat larger scale, generation of the substantial urban or building program is missing; moreover, it does not apply any optimization method for simulation.

Rakha and Reinhart's model (2012) consists of two steps in its workflow, i.e., the generation step and the optimization step, which generates urban form at the district scale. Street patterns and building masses are generated in the generation step using a Rhinoceros/Grasshopper massing tool. The workability of generated urban form is evaluated with a walk score algorithm (Carr, Dunsiger, and Marcus, 2011), and the design is optimized with a genetic algorithm for land-use allocation. This model can be applied to non-flat terrain scenarios; however, only a few limited options for 3D building massing and block pattern (i.e., only rectangular shape) are supported.

Table 7 Comparison of five generative methods for urban design purpose, updated from Singh and Gu (2012)'s investigation

	Shape Grammars	L-systems	Cellular Automata	Agent-based Modeling	Genetic Algorithms
Components	Initial shape/Production rules/Terminal shapes/Operators	Initial symbols/Production rule /Terminal symbols/Operator	Grid and cells/Initial cell states/State rules	Agents/Knowledge base/Action and behavior/ Objects/environment	Alleles/Chromosomes/Genotypes/Phenotypes/Population/Fitness function/Operator
Rule application	Usually, one rule each time	Many rules applied at the same time	Parallel computing process	Usually, one action each time	Usually, one operation each time
Main advantages	Visually defined, usually top-down	Symbolic strings, usually top-down	Bottom-up, context-sensitive	Bottom-up, social behavior, Simultaneous	Optimization, improvement
Main limitations	Incrementally local behaviors are lost	Incrementally local behaviors are lost	Restricted to the geometry of the cells	The outcome is difficult to predict and assess	Usually computationally expensive
Design purpose	Design exploration: space layout and visual compositions	Design exploration: patterns and visual compositions	Grid-based design (planning/zoning). Usability-based, especially context-sensitive design development	Design usability, such as wayfinding. Design evaluation and analysis	Optimization. Design enhancement/improvement. Simultaneously pursuing multiple design alternatives
Design approaches	Emergent shapes and patterns. Geometric shapes.	Use emergent repetitive patterns, fractals, and natural organic forms.	Study of neighborhood effects, growth patterns, social phenomena, etc.	User-centric and use-case designs. Study of social phenomenon, e.g., norm creation, wayfinding, etc.	Combinatorial and morphological designs
Design problems	Architectural styles, objectives and patterns, block layout	Roads and networks, terrains, and texture, building facade	Block design/massing, planning/zoning/urban design	Walkways, public spaces, traffic flow.	Component-based design, optimization problems
Design outcome characteristics	Emergent and exploratory, geometrical. Solutions usually require validation.	Emergent and exploratory, organic, and repetitive. Solutions usually require validation	Emergent and normative, context-sensitive. Usually, satisfactory solutions.	Emergent and normative. Usually, usability driven.	Optimized, usually satisfactory solutions/Multiple design alternatives in most cases
User intervention	High, but mainly in the analysis of outcomes	High, but mainly in the analysis of outcomes	Low, purely bottom-up	Varying with applications. Users may need interaction with design agents	Low user intervention once fitness functions, genotypes, and termination conditions are defined
Development challenge	Difficult to foresee emergent shapes. Emergent shapes may require a new set of production rules.	Difficult to foresee emergent shapes.	Relatively easy to design bottom-up and to identify possible cell states/ neighborhood conditions if the local context is considered.	Varying with the applications and level of the agent's activities.	Problem formulation/ representation and choosing the appropriate alleles, genotypes, phenotypes, and fitness functions
References	Beirão, 2012; Beirão *et al.*, 2012; Duarte *et al.*, 2012b; Gong *et al.*, 2018; Mandić and Tepavčević, 2015; Stiny, 1980	Lindenmayer, 1968; Parish and Müller, 2001; Vanegas *et al.*, 2012	Herr and Kvan, 2007; Neumann, 1951	Bonabeau, 2002; Chen, 2012; Yi and Malkawi, 2012	Haque and Asami, 2014; Kitchley and Srivathsan, 2014; Rivard, Wang, and Zmeureanu, 2006; Yi and Kim, 2015

Yi and Kim's model (2015) focuses on the relocation of tall buildings within their site boundaries using an Agent-based geometry optimization with a Genetic Algorithm to satisfy the intended goal of minimum solar hour access. The model consists of three parts, i.e., geometric modeling, simulation, and genetic optimization for decision making. The first step is the generation of an initial population of random buildings in the NURBS geometry modeling tool. Following that, the geometric information (i.e., building layout) is evaluated by a simulation tool (i.e., using a simulator for calculating direct sunlight hours). In each step, if the generated building geometry's performance does not meet the predefined objective, the next generation is created by changing the building layout from its previous generation. The geometric control using Agent-Based Modeling allows users to find building layout solutions within fixed-site boundaries. This new geometry of buildings is then analyzed by the simulation tool for the change in sun hours, and alternative building layouts are generated until either a layout finds its solution or the predefined number of generations has been reached.

The primary concern in the context of urban growth modeling is to simulate the progress of cities and land-use dynamics. A standard approach is that a large land area is divided into roads and smaller subspaces such as parcels and lots by the land subdivision process. Specific subdivision methods are applied to create spatial layouts, which plausibly correspond to the ones discovered in the real-world urban landscape. In particular, Wickramasuriya *et al.*'s model (2011) and Dahal and Chow's model (2014) automate the process of generating urban layouts such as city blocks, streets, and cadastral lots. A GIS toolset for an automated subdivision of vector-based urban land parcels, the so-called *Parcel-Divider*, offers multiple subdivision styles and can extend roads to new subdivisions (Dahal and Chow, 2014). As a stand-alone application, it can visualize scenarios of infrastructure arrangements in growing areas of the city. The tool can be integrated to accomplish the following task: procedural modeling of 3D urban environments, complemented with *CityEngine* (ESRI, 2019). Constraints such as shape, minimum lot size, orientation, and egress to each lot are applied for the automated subdivision of urban lands.

Vermeulen *et al.*'s model (2015), using the computing of direct solar radiation and an evolutionary algorithm, optimizes the shape and the distribution of buildings inside a fixed rectangular area that are surrounded by pre-existing buildings. Two geometrical models are used to calculate the solar potential over a district and its relationship with urban structure: the one with a grid of buildings in an open area; and the other of dense urban configuration within a pre-existent urban context.

2.5 Limitations of Generative Urban Design Support Methods

In Sections 2.1 - 2.4, the analysis of state-of-the-art research has been presented, aiming to help justify the research purpose for developing the interactive design support method. It is beneficial to examine many design alternatives before a final decision about a design solution is made (Akin, 2001). In this respect, progress in urban design computation has been made with entirely- or semi-automated design methods (Bernal, Haymaker, and Eastman, 2015) by which the design support tools can assist the designer for the tasks of urban layout generation and exploration. i.e., *CityEngine*, which supports the multi-scale (i.e., from a city to a building level), rule-based design and modeling (Parish and Müller, 2001; Vanegas *et al.*, 2012), *DecodingSpaces* (Koenig *et al.*, 2017), and *City Induction* (Duarte and Beirão, 2011).

In general, the synthesis of urban structures follows a sequence of several steps, which are progressed by the generation of a road network, the definition of land use areas, and parcel and building allocation (Lipp *et al.*, 2011; Vanegas *et al.*, 2012). Layout generation for urban scale is implemented in GIS packages (Dahal and Chow, 2014). For example, road network generation to simulate urban growth is accomplished based on L-systems and tensor fields (Smelik *et al.*, 2014). A popular off-the-shelf software, e.g., *CityEngine*, supports the multi-scale (i.e., from a city to a building scale), rule-based design, and 3D modeling (Parish and Müller, 2001; Vanegas *et al.*, 2012). However, the weakness of these procedural methods, which are based on a set of rules, is that the way how designs can be synthesized needs to be described a priori and is seldom related to design issues. Therefore, its application to urban design, which needs to support more dynamic user interaction, is limited.

A subdivision method to create urban structures is enabled in the City Induction project (Duarte and Beirão, 2011). A design methodology based on shape grammar can produce various design variants instead of a single rigid layout in their study. Constraints and rules for the generation of urban design must be specified in advance, and its application to the non-rectangular shape of the plot is limited. The *DecodingSpaces* toolbox (Koenig *et al.*, 2017), a plug-in that is used in Grasshopper, enables the generation of urban design prototypes in Grasshopper, which allows for the synthesis of spatial configurations for road networks, parcels, and building volumes. Using this tool, a designer can synthesize design variants interactively; therefore, the designer can quickly explore many possible solutions. However, direct transformations of urban entities and reuse of previous design solutions are limited.

In this regard, the KREMLAS project is insightful in that it proposes creative evolutionary design methods for layout problems in architecture and urban design (Donath, König, and Petzold, 2012). The concept of the general layout design method was provided, and the essential features for an interactive layout design method such as *adaptivity*, *circularity*, *explorativity,* and *immediacy* are identified as summarized in Table 8. Algorithmic problem solvers using a 2D circle packing algorithm or several 2D layout subdivision algorithms are presented for finding optimal layout structures within pre-defined boundary conditions such as room sizes and neighborhood relationships. In addition to the different forms of representation of spatial elements, the user interaction aspects are considered, and requirements for an interactive generative method were depicted, as shown in Figure 13.

Table 8 The essential features for an interactive layout design method (Adapted from Donath, König, and Petzold (2012))

Features	Explanation
Adaptability	Design problems are not predetermined but are discovered or defined step by step during the design process. The adaptability of a design method is required since the perception of the problems, and the reaction to them develop in parallel in the design process (Schön, 1983). Design problems cannot be mapped on an ad-hoc basis using concrete, ready-made patterns. In contrast to "presented problem situations," the designer has to do with "discovered problem situations" (Getzels and Csikszentmihalyi, 1967). Therefore, a design method must be able to define new requirements for a design problem or change existing requirements during the search process. Adaptive means that the problem is defined as flexible as possible. The prerequisite for such adaptivity is circularity, as is described below.
Circularity	Designing is an iterative process. From a different perspective, every solution found can again pose new problems that need to be formulated and dealt with in further design iterations. However, the order of definition of the problems and the requirements associated with them are not fixed. The ongoing adaptation process does not follow a predefined scheme. It is, therefore, crucial for a design method that works continuously. So, there is no concrete start or end for the solution process, but it must always be in readiness to respond to changing problems.
Explorativity	Generative systems can generate solutions that meet specific operational criteria. These criteria and their weighting can vary with each designer or design. It is crucial that the evaluation function of the generative method can be flexibly defined. Instead of searching for optima for a parameterized problem, the method must be able to flexibly define, modify, and explore a search space on different paths
Immediacy	During the design process, there are phases in which designers calmly reflect on the solution he has worked out, as well as phases in which they try to organize different things simultaneously (Lawson, 2006). They must be able to immediately see the effects of their actions or decisions at crucial moments. Only this immediacy allows an understanding of the effects that are caused by specific changes in rules or criteria.

The KREMLAS project emphasizes that the inclusion of human skills in the computer-based problem-solving process is necessary to optimally use generative methods. The most important aspect is that a user can always intervene in the problem-solving process by examining the solution variants suggested through the system's graphic user interface. It can be accomplished by modifying the problem description, whereby the geometric properties of the elements can be manipulated by direct interaction, and restrictions for the generation can be modified by indirect interaction.

All things considered, the entirely automated or semi-automated generation of the urban space design that is summarised above seems to consider the human aspects less. Moreover, design variants that are obtained during each concept development stage are seldom re-used for the generation of new design variants or the evaluation of other working variants. Current design support methods that are developed for urban design seem to be weak in reflecting the iterative nature of the designer's creative problem.

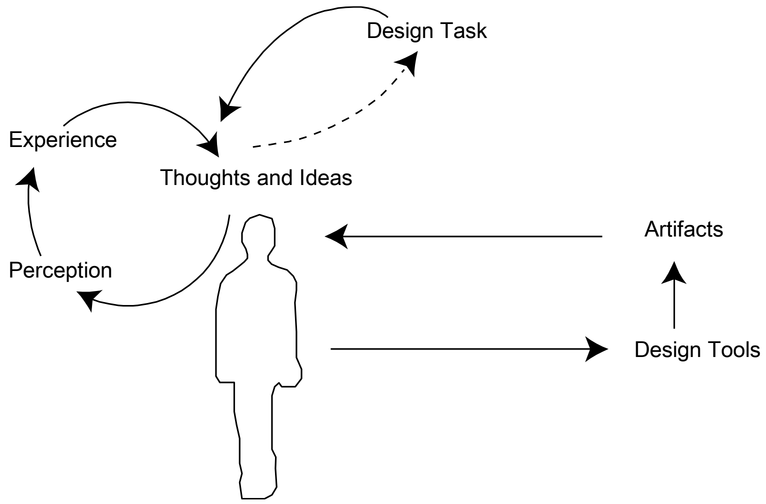

Figure 13 Design cycle as a user-design tool interaction (Donath, König, and Petzold, 2012, p. 38)

In the following, I present a novel approach to encourage a designer's creative activity by providing the explorative capability, particularly for solving the urban masterplan's design tasks. Given an urban design task, a designer can place urban entities (e.g., buildings, plots, streets) at the intervention site using the proposed urban design support. In the proposed design support, a human designer can directly manipulate the urban entities' geometric properties and modify restrictions for the generation indirectly. The urban design support can quickly evaluate the design stage's state and suggest alternative design variants to the designers, which allows designers to generate more various candidate concepts. A method to keep track of and reuse the generated design ideas through design history management is proposed, allowing for spontaneously shifting back and forth between different ideas. Therefore, the proposed urban design support concept is that a designer can involve in design authoring activities, and the design support can suggest alternative solutions quickly. A detailed explanation of the design support methodology will be introduced in Chapters 3 and 4. Also, the development of computational design support methods might be improved if informed by detailed knowledge of design cognition.

3 Integrated Urban Design Support

This chapter proposes an integrated urban design methodology, which can provide configurational information and a level of interaction to assist the authoring activities for urban space design. Section 3.1 provides the scope of the proposed urban design support. Section 3.2 formulates the urban design's typology, characteristics of the masterplan, urban design operations, and entities. Section 3.3 highlights the support for urban design performance evaluation, and Section 3.4 proposes a computational urban design support methodology, focusing on design generation, transformation, and variants synthesis.

3.1 Conceptual Framework for the Proposed Urban Design Support

The urban design support is a computer-based, interactive, urban design generation with human designers central to the design development, as represented in Figure 14. The design support aims to encourage a designer's creative activity by providing the explorative capability for the urban masterplan and stimulating the human designer's inspiration. How designers develop solutions to problems is vital for devising techniques for computer-based design support. Given an urban design task, a user (a human designer) can place design entities (e.g., blocks, plots, streets, and buildings) at an intervention site using urban design support. The urban design support can quickly evaluate the design stage and suggest alternative design solutions. The design support can also provide some critical analytic results such as spatial visibility (openness), density, street connectivity, and daylight, which are essential aspects to consider during the early urban design process.

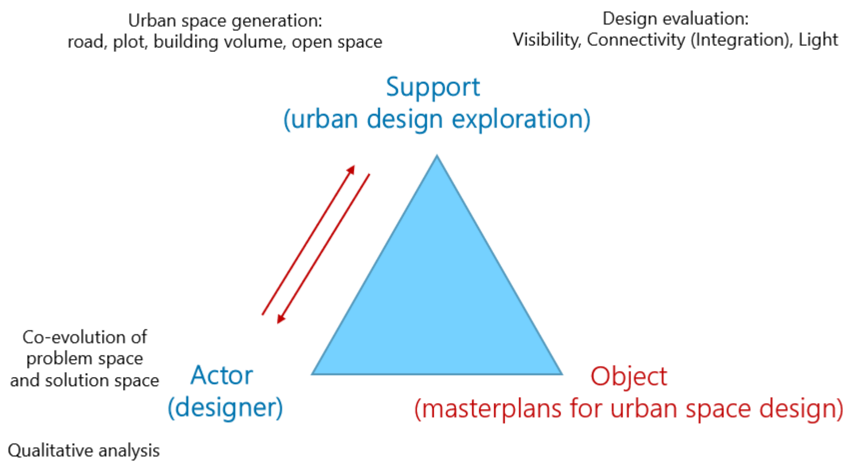

Figure 14 The scope of the proposed support for interactive exploration of urban design

As the design process is conducted cyclically, human designers can perform design actions based on the design support's feedback. This procedure will be continued until the design assignment ends. Therefore, urban design support has a more significant potential for explicit support for reflective design thinking and bi-directional information exchange. What can be expected is that a user may practice informed decision-making while preserving ownership during the design process, which can assist in designer-led creative design activities.

3.2 Formulation of Urban Design

3.2.1 Typology of Urban Design

The term 'urban design' is used to refer to the process of designing urban places. In this regard, the urban design aspects include physical and social, cultural, and economic dimensions, as discussed in Subsection 2.3.2. As many interest groups, tools, and activities in a different context are involved in urban design activity; it is necessary to set up a boundary (or limit) that the proposed method intends to support more precisely (and in the more limited sense used in this research). Of course, it does not mean that other activities are somewhat negligible.

First of all, to prove the research concept, it is considered to formulate a specific type of urban design. The typologies of the urban configuration that is mainly supported in this research are a block structure (layout) and grid structure, which can be extendable to other types of the urban layout. In particular, the block layout is accepted as one of the dominant patterns for urban layout in the US and the European countries, which is frequently practiced until recently by many contemporary urban firms (Adam and Jamieson, 2014). The block layout has merits because of the physical structure. For example, a courtyard enclosed by a building volume enhances safety and community activities. Also, its continuous pedestrian movement can bring vitality to the street. The design support is intended to help the design activities for masterplans, which are the form of urban design tasks that are used increasingly in urban development and regeneration (Tiesdell and Macfarlane, 2007). Of course, the users of the design support can develop unique urban configurations using simple functions that will be introduced later.

Different levels of design activity and tasks can be the focus of the study. However, the proposed urban design support can mainly address the "*second-order design activity*" (George, 1997). Also, first-order design activity that focuses on the direct manipulation of design objects can be supported in the proposed framework. Discernible from the second-order design activity, the first-order design activity in urban design is providing a ground scheme that can be used as a base for the detailed urban design in the later design stage. In order to support the first-order design activity for master planning, different typologies of urban master planning are analyzed. The proposed design support prototype will be used to test how it can help human designers with idea development; it is necessary to include several typologies, which do not limit the designers' design activity.

3.2.2 Characteristics of Masterplan

First, it is necessary to discuss the difference between architectural/building design and urban design. Architectural/building design is related to the "first-order design" activities in which designers have a direct relationship with the designed object (George, 1997). For this, designers focus more on the design and development of a single plot/land parcel (George, 1997). On the other hand, urban designers have an indirect relationship with the designed object, which is called the "second-order design" activities. As discussed previously in Section 2.3, the focus of the urban design is the design and development across plot/parcel lines, i.e., the design of the physical setting of urban places by relating 'parts' (i.e., individual buildings) to a more substantial 'whole' (i.e., the place) (Tiesdell and Macfarlane, 2007). Therefore, urban designers mainly involve in creating a decision-making environment where others author the built environment, as shown in Figure 15. As such, the purpose of the masterplans is to control the form-based and site-based development by meditating on parts and the whole (George, 1997).

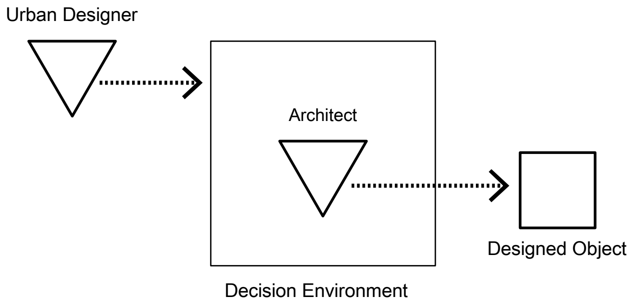

Figure 15 The relationship between the urban designer and the designed object (George, 1997)

Apart from architectural/building design aspects, the urban design includes the basic three-dimensional form, massing, and positioning of the plot. Besides, site-specific built-form relationships are defined by street and building lines and height. More detailed specifications can be provided on a smaller spatial scale as a form of design briefs, which include volume, massing, floor space, and uses. Of course, infrastructure, the public realm, and open space are to be prescribed in the masterplans (Tiesdell and Macfarlane, 2007). In most masterplans, a set of rules are provided in order to control the form-based and site-based development. The urban code sets up the baseline of the urban space and built-form such as height, massing, positioning on the plot, and so forth (George, 1997, p. 150). These parameters of urban elements are modeled in Subsection 3.4.1.

3.2.3 Methods to Relate Parts to the Whole

The methods which enable human designers to relate individual parts to a larger whole, as the "second-order design," need to be determined to implement them in the prototype. Wienands (1985) identified three basic methods (operations) that are mostly used to relate the parts to the whole – i.e., additive, divisional, and superimposing approaches by analyzing contemporary urban design projects. These basic methods allow for making diverse variants of street grids, as shown in Table 9. In the additive approach, the parts are defined in advance before assembling them into a whole. Of course, the parts can be entire urban districts, individual building plots, or urban blocks depending on the scale, function, and design intent. The parts assembled to form a whole can be equal, similar, or heterogeneous to each other and can be assembled flexibly, which must not necessarily depend on a grid pattern (Schenk, 2013). However, its shortcoming is that, when repeatedly applied without care, the outcome in its entirety can be monotonous. It can also be difficult when it comes to adapting these parts to the topological aspects of the design site.

With the divisional approach, the overall form of the whole can be described before defining the parts. Depending on the objective and function, the whole is divided into parts by applying specific rules. For example, the divisional approach's merit is that the approach can optimize overall physical features, appearance, and design qualities. However, it is considered that new parts cannot be added or removed flexibly as the parts are fixed/related rather firmly to the whole (Schenk, 2013). Furthermore, the geometric constraints from the application of the divisional approach can have adverse effects on the design by weakening the proper functioning of the parts. As such, these weaknesses can be resolved by mixing other methods. In some cases, the additive approach can be applied partially, or individual parts can be merged into the group (Schenk, 2013).

Table 9 Variation of street grids (Source: adapted from Schenk, 2013)

Street grids	Typical quality/features
Regular grid	Square or rectangular Rationally divided in the orthogonal system without creating unwanted residual areas
Irregular grid	Divided at more regular intervals along one direction and more irregular intervals in the perpendicular direction
Tilted grid	Portions of the grid are tilted against one another depending on the topography and the orientation.
Deformed grid	Non-orthogonally laid-out patterns, e.g., stretched, or curved grids
Transformed grid	The overall layout structure follows the orthogonal system but is further divided into an irregular pattern
Superimposed grid	Layering multiple systems of order

With the superimposing approach, the urban layout is generated from the overlays of multiple urban patterns. This approach can complement both the additive and divisional approaches by creating an enriched spatial experience (Schenk, 2013). When applying the superimposing approach, however, a particular scale of the project needs to be considered.

In addition to the additive, divisional, and superimposing approaches, Schenk included “urban design as a single entity (or grand form)” as a major design approach. The characteristics of the grand form lie in a single entity in which individual parts are combined into an overall form. The overall configuration can be transformed *1) by applying an additive approach if started with individual components, 2) by applying a divisional approach if started from a single form, or 3) assumably by applying multiple approaches*. Such a grand form approach allows for achieving more design organic/biomorphic or free-form urban design. As a proof-of-concept, these three design approaches are implemented in the design support prototype, as discussed in Section 3.4.

An urban block is defined by surrounding streets that are envisaged mainly as pedestrian spaces or partially car parking. The infills that will be designed and developed in the urban block influence the surrounding streets' design and vice versa. Based on the description of the urban masterplan entities, the significant entities such as block, plot, building, open space, and road network are included in the formulation of urban design components, as shown in Figure 16. These masterplan components are interfaced with each other and deal with '*the arrangement of the physical objects and human activities which make up the environment*' (Bahrainy and Bakhtiar, 2016). For instance, the space between buildings influences principally outside activity and the environment. The building volume is represented in the X, Y, and Z Cartesian coordinate system, which enables assessing a few qualitative aspects of the urban space.

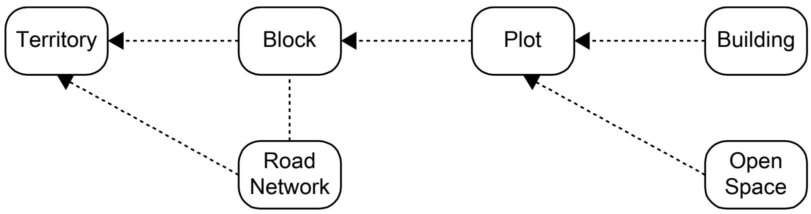

Figure 16 Hierarchical structure of urban components

3.3 Support for Urban Design Evaluation

Problem-solving in urban space design is a kind of design problem; therefore, it seems many urban space design characteristics are in common with those of wicked problems. Some aspects of urban space design are evaluated rather often in concept development by human designers. Regarding the quality analysis of urban space design, some aspects of urban design considerations can be conducted computationally, for example, by using geometric property taken from the urban configuration. Some analytic tools are available to evaluate urban space design, such as quantitative analyses for visibility (openness), density, connectivity, and environmental quality are considered in this research, among other things. These analyses are admitted in the prototype as they can be performed quickly. Even seldom standardized, however, such properties are considered of importance during evaluation steps in most urban space designs.

3.3.1 Visual Quality Evaluation

Urban designers concern the masterplan's visual quality as it is one of the dimensions that humans perceive and experience urban space. Urban researchers and practitioners have widely accepted the assumption that the human's spatial perception is structured by physical properties such as urban form or urban spatial configuration for decades (Benedikt, 1979; Fisher-Gewirtzman, Burt, and Tzamir, 2003; Lynch, 1980; Turner, 2003; Yang, Putra, and Li, 2007). The idea implies that human perception is influenced by the physical properties of the urban form. It also suggests that it is crucial to evaluate design decisions' visual impact on the existing or proposed urban form (Yang, Putra, and Li, 2007). Batty (2001) argued that the issues related to the visual quality such as `*how far can we see,'* `*how much can we see*,' and `*how much space is enclosed*' are the keys to developing a good urban design. Table 10 shows attempts that have been made to compute the visibility of urban space in 2D and 3D. They are motivated by the traditional methods that have been proposed by Cullen (1961), who proposed a visual analysis method by recording sequential order of visual experience on the street level, and Lynch (1980), who proposed the idea of developing computing systems for delineating view field, creating diagrams for intervisibility and view access.

Table 10 Visibility analysis methods

Method	Application area	Details
2D isovist	Visibility in architecture and urban space (Benedikt, 1979)	A set of points in 2D space that are visible from a vantage point
Cumulative isovist	Visibility analysis to the indoor space and urban space with the use of agent-based simulation (Batty, 2001; Turner, 2003)	A 2D horizontal slice of the view
Viewshed	Landscape analysis with the terrain and topographic differentiation (Llobera, 2003)	A terrain visible from a major viewpoint. The grid cells that can be connected by means of the light of sight to a viewpoint
3D Viewsphere visibility analysis	Evaluating the visibility of urban design scenarios and their potential impacts on the visual quality of open space (Yang, Putra, and Li, 2007)	A visible volume, which is filled with the ambient optic array
Floor Green View Index (FGVI)	Measuring urban dwellers' view-based exposure to greenery (Yu *et al.*, 2016)	An area of visible urban vegetation observed from a certain floor in a building

When considering the efficiency and availability of visibility (openness) algorithms, Asano (1985)'s analysis method for visibility polygon for polygon regions with holes is integrated into the design support prototype. Of course, Various methods for visibility analysis have been introduced but are not practical to be used in design tasks as they are computationally expensive. Another consideration is that a specific type of data format must be prepared to apply those methods. Simple but continuously influenced properties such as how much area and how far distance can be seen from a specific viewpoint are the common questions that designers frequently ask during an early stage of urban space design. In order to measure the area that is visible from the point of a building façade and the area from a location in the open area, Asano (1985)'s analysis method for visibility polygon for polygonal regions with holes are adapted by mapping polygonal regions with the urban area and the holes with individual buildings. The detailed steps of the algorithm follow the description by Ghosh (2007) and Berg *et al.* (2008). In order to run this visibility algorithm, it is required to conduct the pre-processing of trimming unnecessary areas around a point of interest. This method is implemented in the design support prototype to be used along with other operations if necessary conditions are satisfied.

3.3.2 Urban Density Evaluation

The density measure is used as a tool to inform, analyze, and control urban design and development goals. It is relatively common to develop urban (master-)plans for specific density goals. For this, urban designers go through interactive negotiation processes with stakeholders based on the plan and the respective density goals until the agreement between them is made. The density indicator acts as a constraint that must be considered during the design process for limiting the volume of development on any given plot.

The most common measure of building density is the Floor Area Ratio (FAR), also known variously as 'floor space index (FSI),' 'floor space rate (FSR),' or plot ratio, which indicates the ratio of total floor area to land area. Only with FSI, the building height cannot be controlled. When a fixed FSI is given, it is possible to design a building with high-rise low-density or low-rise high-density. Therefore, 'building coverage ratio (BCR),' maximum/minimum building height, and setback are used as parameters for controlling the density in different circumstances. Different parameters may be combined to achieve particular effects. The number of dwellings per square kilometer is another standard measure of density, which allows for assessing the population and building densities together. In the seminal book "*The death and life of great American cities*," Jacobs discussed four factors (i.e., mixed uses, aged buildings, small blocks, and population density) in city planning and design which make the city diverse, safe, social, convenient, and economically vibrant (Jacobs, 1961).

In particular, she described the relationship between various densities and urban diversity and argued that the density which enables high levels of street life and walkable access to diverse amenities is a necessary (but insufficient) condition for urban vitality and safety. For example, she advocated high levels of site coverage (a sufficient concentration of buildings to attract people and a minimization of vacuum areas) as she viewed that the high-density and low-rise development can create greater variety than a modernist tower typology. Berghauser Pont and Haupt (2010) have developed a matrix of three geometrical properties of buildings: density as a floor space index (FSI), ground coverage, and the number of stories. They suggested the measure of an 'urban footprint' as the total amount of floor space per resident in a given area. And they suggested a model of '*Spacematrix,'* wherein the density is treated as a multivariable phenomenon, consisting of the three fundamental variables: FAR, Coverage, and Network Density.

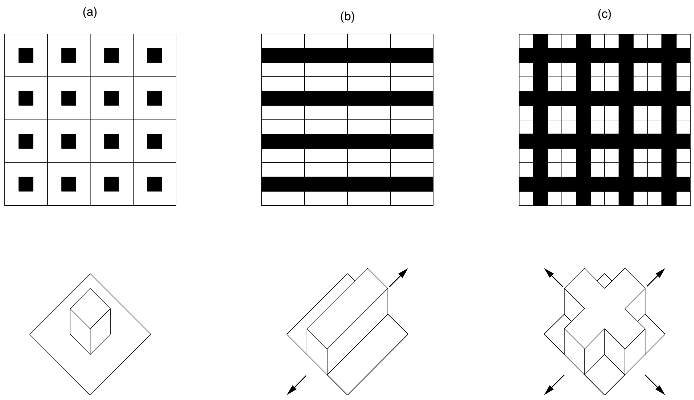

Figure 17 The comparison of the performance in terms of density and ground coverage of three generic forms of building: (a) 'pavilions,' (b) 'streets,' and (c) 'courts' (Martin and March, 1975, p. 36)

Moreover, it is known that urban density is related to energy issues. So, in the early design stage, when detailed information is not ready and an approximated measure is needed, urban density measure can be indirectly used to guess the environment's energy performance promptly. The use of different analysis methods is limited in the early design stage. Hui (2001) emphasized the negative impacts of density on natural light, solar gain, and ventilation as important trade-off factors. Designers may use the relation between the ratio of built area to site area and the availability of daylight has been studied, as shown in Figure 17. Several evaluations of urban density can be provided to the users. Moreover, the users can achieve a specific level of an intervention area's density by applying an automated method for densifying a chosen area.

3.3.3 Connectivity Evaluation

The street network's connectedness in the design area needs to be considered as a range of benefits can be obtained from a well-connected street network. It is known that areas with high connectivity make it easy for each goods, service, activity, and destination, which together are called "*opportunities*" (Litman, 2007, p. 4). Also, connectivity is related to pedestrians' activity level as areas with more significant connectivity provide more direct routes and, therefore, shorter travel distances to destinations (Ellis *et al.*, 2016; Hess *et al.*, 1999; Ozbil, Peponis, and Stone, 2011). Connectivity can contribute to diminished arterial traffic, better access for emergency vehicles, and cheaper utility connections and services (Handy, Paterson, and Butler, 2003). Of course, the relationship between the built environment and physical activity is not simple to grasp, but it leads to 'walkability,' which includes physical aspects such as 'time and efforts' and comfort, safety, and visual aspects. According to Southworth (2005, p. 248), walkability is defined as "*the extent to which the built environment supports and encourages walking by providing for pedestrian comfort and safety, connecting people with varied destinations within a reasonable amount of time and effort, and offering visual interest in journeys throughout the network.*" It is widely accepted that an area with a highly connected path network (i.e., allowing easy and direct routes between origins and destinations) and a high degree of proximity (i.e., many functional spaces can be accessed within walking distance) encourages people's walking (Southworth, 2005), which is known to contribute to various health benefits (Hamer and Chida, 2008).

In order to measure the walkability in an urban context, various metrics such as 'intersection (node) density,' 'Link-node ratio,' Pedestrian route directness,' 'Pedshed,' 'Metric reach,' and 'Directional reach' were developed for objectively evaluating the connectivity of the built environment (Ellis *et al.*, 2016). Among others, 'metric reach' and 'intersection density' appear to reflect well actual levels of physical activity of residential areas (Ellis *et al.*, 2016). These two different connectivity measures can be used to evaluate and monitor the actual physical activity levels in urban areas and may be used to better support decision-making in urban space design. The metric reach is defined as the total length of the network that can be reached by walking in all possible directions from a location of origin. It fundamentally measures the density of available footpaths within a specific threshold. The greater the value of the metric reaches, the higher the connectivity of a specific location in the built environment is. Peponis et al. (2008) formulate the "*metric reach $R_v(P_i, \mu)$ of a point P_i according to a metric threshold μ as the length of the road segments and tractions of road segments covered by the union of all paths for which $s \leq \mu$" with "no line segment or fraction of line segment is counted twice,*" as shown in Figure 18.

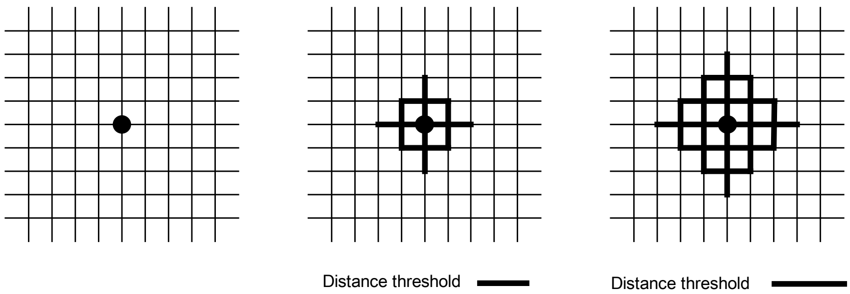

Figure 18 A diagrammatic definition of metric reach (Peponis, Bafna, and Zhang, 2008, p. 883)

An additional metric to measure the connectivity is the intersection density, which represents the number of intersections (i.e., where more than two links are incident) per unit area (Ellis *et al.*, 2016), as shown in Figure 19. A larger number of intersections per unit indicates greater connectivity and vice versa. A buffer or network distance around a specific location in the built environment is used, such as 1000 meters (equal to 10 minutes walking distance), 500 meters (equal to 5 minutes walking distance).

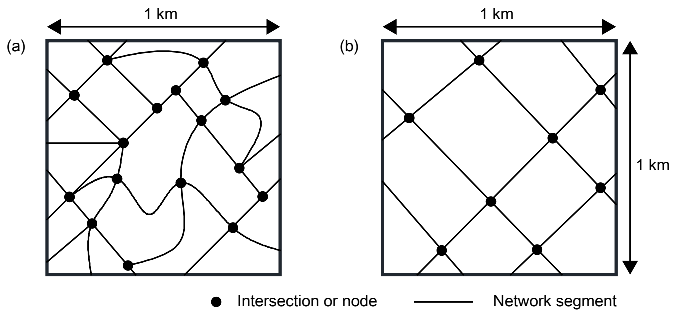

Figure 19 Intersection density: (a) 16 intersections per square kilometer, showing higher connectivity, and (b) 8 intersections per square kilometer, showing lower connectivity (Ellis *et al.*, 2016)

3.3.4 Environmental Quality Evaluation

Environmental quality is also one aspect that is frequently to be considered from the early design phase[7]. For example, the urban (re)development composed of dense and high-rise buildings can result in the infringement on the right of light, which can be detrimental to the living condition. In addition, design proposals that do not consider the insolation and daylight of buildings and the open spaces may cause uncomfortable living conditions both inside the buildings and in the streets. Therefore, designers deal with geometric characteristics of the plot, street, building volume, and open space, i.e., their profile, volume, distance in-between, and so forth, which have a significant influence on the environmental quality, i.e., daylight availability of the masterplans. The most modern urban design must consider the environmental sustainability related to daylight and insolation to achieve pleasant living conditions and improve urban comfort. For this purpose, mutual shading between buildings and other elements, e.g., trees, must be analyzed during the different times and throughout the year as the daylight analysis in urban areas is essential in establishing the benefits to be obtained from the sun (Pereira, Silva, and Turkienikz, 2001, p. 217). However, in the early urban design stage, some designers tend to simulate the direct solar potential of a site's unoccupied volumes to maximize the incident solar radiation. Several parameters, such as the Sun path, the geographical feature, and the surrounding objects, are essential to simulate the direct solar radiation on a planned site. The Sun's trajectory can be

[7] Building energy consumption in the urban context is dependent on the five factors (i.e., urban climate, urban morphology, building design, HVAC systems, and occupant behavior), according to Baker and Steemers (2000), and Ratti, Baker, and Steemers (2005). Among the factors, it should be noted that urban morphology is under the control of urban planners and designers; therefore, designing and sizing urban districts from the early design stage should include the design ideas that may enhance the energy and environmental performance of urban morphology. For example, Lobaccaro *et al.* (2017) proposed a set of urban design recommendations to enhance solar accessibility and demonstrated the optimized urban morphology (considering metrics such as building massing, density, and orientation) increases the buildings' solar potential through a case study.

calculated by using the site location, the day of the year, and the time of the day. The geographical feature includes the local altitude and the climate type of the site. Buildings, topography, and vegetation are included in the surrounding objects. In order to calculate the shape of a shadow, knowledge of the position of the Sun is needed. To begin with, the direction of the Sun is calculated using the solar zenith angle, ϕ_{sun} (the angle between the vertical and the line to the Sun), and the azimuth angle ψ_{sun} (the horizontal angle between the South and the vertical projection of the Sun). These angles depend on the latitude of the site, φ, on the solar declination, δ, and the solar hour, expressed as hour angle, ω. More details on the calculations of the solar declination and the solar hour are described by Kalogirou (2014).

Table 11 Methodology for the simulation of the direct solar radiation after the setup of site parameters

Step 1: Prepare a collection of triangles from urban objects. Step 2: Prepare points subdividing the site area with a chosen distance gap. Step 3: Prepare rays over the chosen period with the chosen time step.
For each point
For each ray
For each triangle, Step 4. Test ray-triangle intersection and if the ray reaches the point, then add ray values to the current point
Next
Next
Next
Step 6. Visualize results

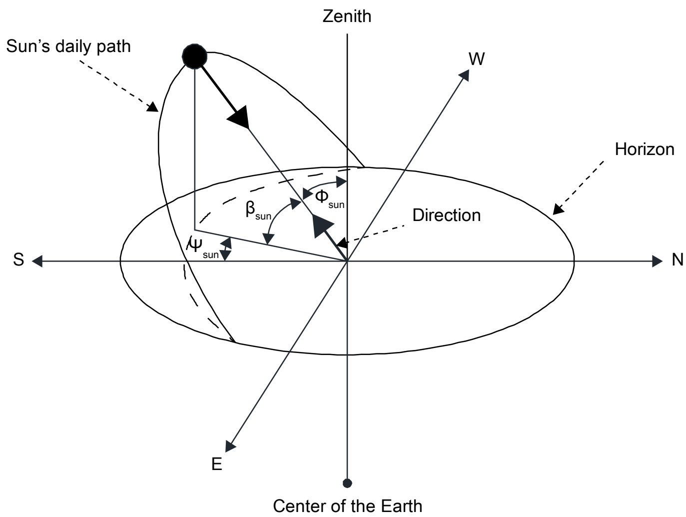

Figure 20 The solar path across the sky from sunrise to sunset

The solar altitude angle (β_{sun}) is the angle between the Sun's rays and a horizontal surface. Therefore, $\Phi_{sun} + \beta_{sun} = \pi / 2 = 90^{\circ}$, $\phi_{sun} = \cos^{-1}(\cos\varphi\cos\delta\cos\omega + \sin\varphi\sin\delta)$, $\psi_{sun} = \mathrm{sgn}(w)|\cos^{-1}\left(\frac{\cos\phi_{sun}\sin\varphi - \pi n\delta}{sin\phi_{sun}cos\varphi}\right)$. The equation of a surface, α, with normal vector $\vec{n}$ through the origin (0, 0, 0) is $ax + by + cz = 0$, where the components of the normal vector $\vec{n}$ can be calculated from the orientation and the tilt angle of the surface is $\vec{n} = (a \quad b \quad c) = (\cos\gamma\sin\Sigma \quad \sin\gamma\sin\Sigma \quad \cos\Sigma)$. Of which γ is the azimuth of the surface (angle between the

South and the normal to the surface), and Σ is the tilt angle of the surface. If the surface contains three points A, B, C, the normal vector to the plane is calculated by the cross product of $\overrightarrow{AB}$ and $\overrightarrow{BC}$. Figure 20 shows the parameters for calculating the solar path across the sky from sunrise to sunset.

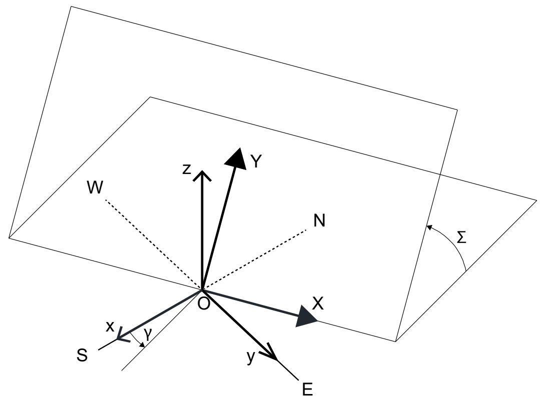

Figure 21 Coordinate system for the calculation of light projection on a surface

The projective line (solar vector) from the Sun can be determined by the solar azimuth angle, ψ_{sun} and the solar altitude, β_{sun}, where the components of the solar vector $\vec{\boldsymbol{s}}$ are $\vec{s} = (l \quad m \quad n) = (\cos\psi_{sun}\cos\beta_{sun} \quad \sin\psi_{sun}\cos\beta_{sun} \quad \sin\beta_{sun})$. If $\vec{n}\cdot\vec{s} > 0$, the sun is above the surface, then direct radiation impinges on the surface. When f $\vec{n}\cdot\vec{s} < 0$, then no direct radiation impinges on the surface. The equation of the straight line that projects a point onto the surface can be determined. Given a point $P(x_0, y_0, z_0)$, thee parametric equation of the projective line $\bar{r}$ is given by $\bar{r} = (x \quad y \quad z) = (x_0 + l\cdot t \quad y_0 + m\cdot t \quad z_0 + n\cdot t)$. The point $P'(x_0', y_0', z_0')$, projection of P onto the plane along the straight line $\bar{r}$, are given by the intersection of $\bar{r}$ with α, to be solved in terms of the parameter $t = -\frac{ax_0+by_0+cz_0}{al+bm+cn}$.

Figure 21 shows the coordinate system for calculating the light projection on a surface. In order to check if the rays from the Sun hit against the building block, points on each elevation of a building are generated for a certain gap. A set of the solar rays are calculated for a time period and a time step (e.g., 10 minutes), which is defined by the user. As the tilted elevation of a building is not considered, Σ is set to zero. Lastly, it is necessary to check if the point P' is inside the surface, and the rays are obstructed by other surfaces. The brief concept for sunlight analysis is discussed so far. Evaluation methods for other aspects, such as wind flow and pedestrian flows, for which dynamic simulation is needed, are not included because they are not used during the early design stage. Furthermore, those methods tend to need more detailed information, which is not available in the early design stage; therefore, it may be difficult to obtain a meaningful result.

3.4 Urban Design Generation Support Method

This Section prescribes methodologies for supporting urban design development. Subsection 3.4.1 prescribes urban design generation and transformation operations that human designers can use, based on the ideas in Section 3.2. Furthermore, Subsection 3.4.2 demonstrates several urban variants synthesis methods by which urban designers can be supported interactively for design exploration.

3.4.1 Urban Design Generation and Transformation Operations

The generation and the transformation of urban fabrics are realized through the user operations in the implemented urban design support prototype. Table 12 provides a summary of design generation and transformation methods for urban masterplans. As the design support prototype is used to prove the research concept, only necessary operations are selected for the prototype implementation as follows:

- **Axis insertion:** Lines that represent various axes are considered as a seed to generate diverse urban entities such as site, network, road, and view corridor. An axis is represented by the connection of two disjoint points that are given manually. When the intervention site's boundary information is loaded, the designer can add more axis lines to be used as a basic sketch or measure the distance between two locations.
- **Axis modification:** For supporting simple CAD authoring, two approaches for modifying an axis are implemented, such as the one is to drag a line segment from the origin location to the destination, and the other is to drag a vertex of the line segment. If a particular modification on a selected axis is observed in the design support, any other urban entities that are connected with the axis line or are influenced by the axis line segment are updated by considering the property change.
- **Axis deletion:** When the axis deletion option is selected, the deletion of an axis is performed by calculating the distance between the selection point and the axis. If the distance is within a threshold given, the selected or the closest axis line is deleted. Of course, as is the "Axis modification," any other entities in the design support that influence the line or are influenced by the deleted axis line are updated by considering the property change.
- **Axis connection:** "Axis connection" is to build a polyline by connecting two axis lines that cross each other. Under the option selected, first, two-axis lines must be selected and checked whether they cross at an intersection with each other. If the intersection point of the two-axis lines is detected, the intersection point becomes the middle points of the polyline, of which endpoints are taken from the endpoint of the respective axis lines.
- **Block/Plot division:** By using the network information as an input for land divisions, the intervention site is divided into urban blocks/plots. For example, blocks or plots can be

divided into multiple ones if they have more than two crossing points. Figure 22 demonstrates the application of the “Block division” operation, by which two blocks are divided into four blocks. A Half Edge Data Structure (abbr. HEDS) (Brönnimann, 2001) is adapted to represent the outcome's geometric base data, by which it enables to handle incident entities of a selected entity for various purposes. After executing this operation, the entities that are subordinate to the affected ones are removed, and the resulting entities inherit the properties (e.g., usage, density, and offset distances) of their source entities. Moreover, neighboring entities are updated to maintain the entities’ consistency because their geometric and topological relations are transformed.

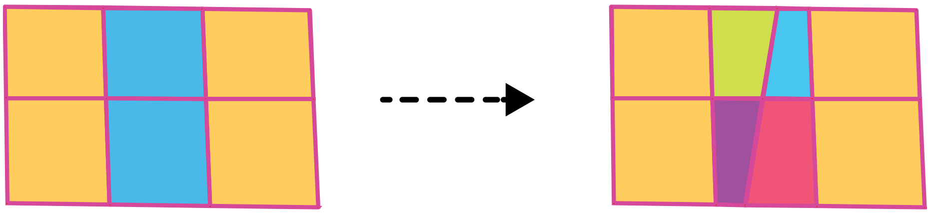

Figure 22 A example of a block division

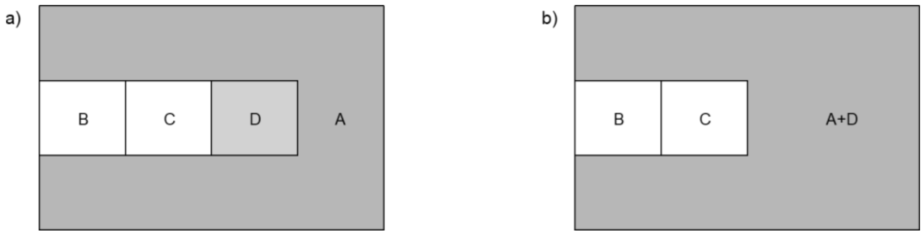

Figure 23 A example of a block merge

- **Block/Plot merge:** Any two incident blocks/plots are divided by at least one axis line. If the selected two entities are identified incident, they can be merged into a larger one under the “Block/Plot merge” mode. When the designer runs the merge operation, the first selected entity's properties are copied to the combined entity. However, just like the case of the Block/Plot division operations, the entities that belong to the source entities are removed, and their neighboring entities are updated. Figure 23 demonstrates the application of the “Block merge,” of which image b) is the result of merging block A and block D of image a). Between block A and block D, three edges are shared, and they form a continuous chain of edges. However, there is one limitation concerning the use of this operation. In Figure 23 a), the merge between block A and block C (also, between block A and block B) is not permitted because they are incident, but through two noncontinuous series of lines. If this is allowed, there will be the remaining blocks that are fully enclosed by the merged one. Such a case among the same entities is rare in the real world; therefore, a particular feature such as a hole of a polygon is not implemented in the urban design support prototype.

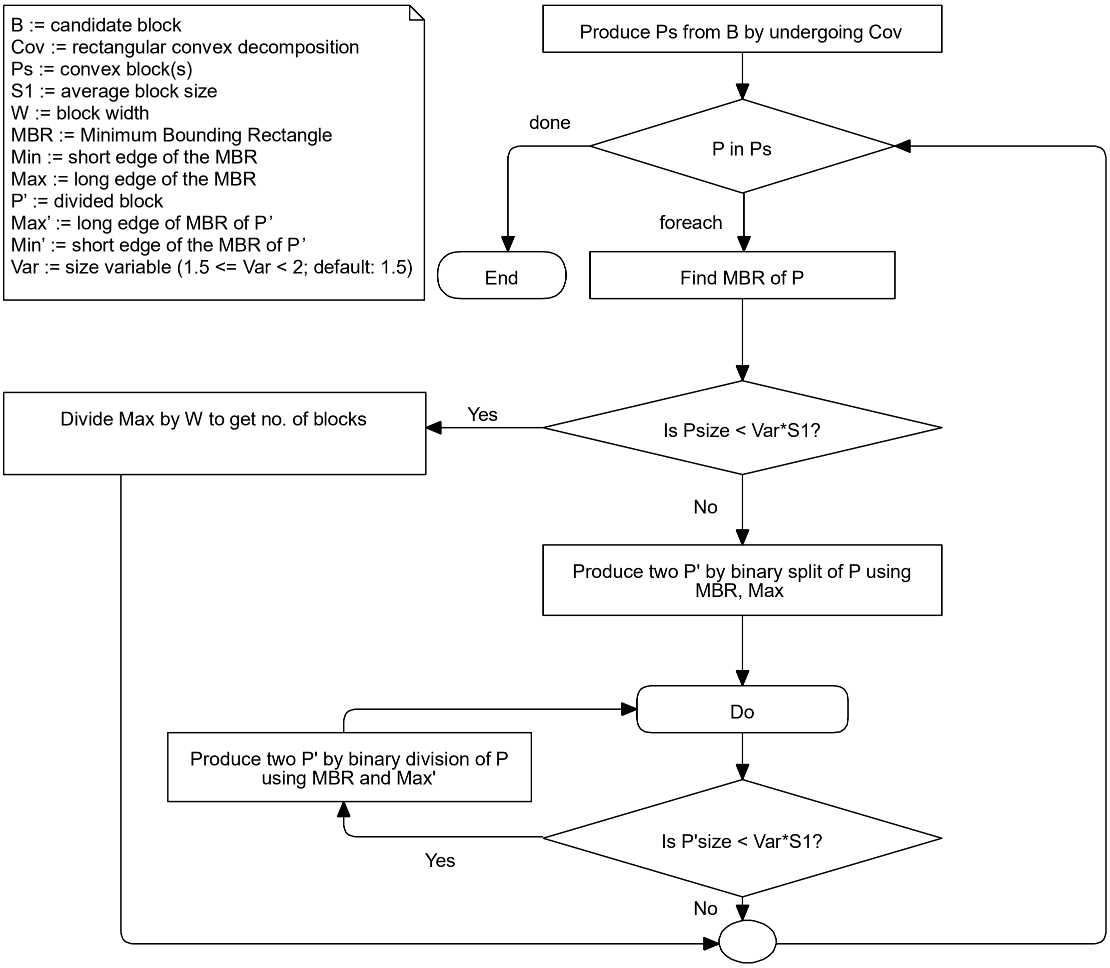

Figure 24 An algorithm for block subdivision using binary partitioning and MBR

- **Block subdivision:** A candidate block is subdivided into blocks by considering the size, shape, and dimensions, as shown in Figure 24. First, the selected block is decomposed into smaller ones (i.e., convex block(s)) by using a rectangular convex decomposition algorithm. Furthermore, the rest of the procedure is to split blocks until their size and dimensions become less than user-defined values. In this case, the "Block/Plot division" operation is applied by referencing the line segments that are calculated for splitting the candidate block.
- **Block subdivision into plots:** Plots that are inside of a selected block are generated by considering the size, shape, and road network. Three kinds of block typologies are implemented: 1) Gridiron system, 2) Perimeter block housing, and 3) Block tower, as shown in Figure 25.

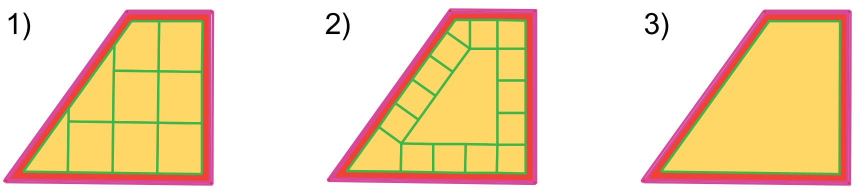

Figure 25 Three kinds of block typologies generated in the same block area

Table 12 Design generation and transformation methods for urban masterplans

Name	Command Name	Description	Input	Output
Axis insertion	InsertAxis	A line that represents an axis is inserted by two points. The axis is used as a baseline for street generation and land subdivision.	Two points	A new line
Axis modification	ModifyAxis	A line that represents an axis is modified by dragging an endpoint to a new position. All incident entities are modified as a result.	A line and two points	A modified line
Axis deletion	DeleteAxis	A line that is the closest to a point is deleted.	A selected line	NULL
Axis connect	ConnectAxis	Two disjoint axes are connected by extending one or two axes until they are connected. The connected axis increases network connectivity.	Two axes	Connected axes
Block/Plot division	BlockDivision PlotDivision	Block(s)/plot(s) are divided into multiple blocks (s)/plot(s) when intersected at more than two locations by a line.	Polygons and lines	Divided Polygons
Block subdivision	BlockSubdivision	Using the land subdivision algorithm	Polygons and neighboring entities	Divided Polygons
Block/Plot merge	BlockMerge PlotMerge	If the selected entities are incident, then they are merged into a larger one.	Polygons and lines	A larger land
Street addition	AddStreet	A local access street is added.	A line and incident entities	A new access street and modified plots
Public space insertion	InsertPublicSpace	Public space is inserted into a vacant plot, a portion of the building footprint, or a road intersection.	A vacant plot, a portion of the building footprint, or a road intersection	A new public space
Block densify	BlockDensify	A selected block is densified with parameters the GFA and building offset distance.	A selected block	A block with updated buildings
Block subdivision into plots	SubdivideBlock	A selected block is subdivided into plots by considering the size, shape, and road network, i.e., gridiron system, perimeter block typology, and tower block typologies	A block and neighboring entities	Plots and road network
Building generation in a block	GenerateBuildingInBlock	Perimeter block houses are generated in a block by considering the maximum height allowed.	A block and neighboring entities	Blockhouses
Building generation in the plot	GenerateBuildingInPlot	A semi-/detached house is generated in a plot.	A plot and neighboring entities	House(s), e.g., a semi-/detached house
Building parameter modification	ModifyBuildingParameter	E.g., building height and possibly a quantitative requirement.	A pre-existing building	A new building

- **Building generation in a block:** In a block, a building footprint pattern is generated by considering the offset distance, density, height, and building code. Diverse building footprints can be developed, but only offset from each plot in a selected block is used to generate one. In order to prevent generating a building with a remarkably tiny footprint, a building in a plot can only be generated if the size of the building footprint is larger than a threshold defined.
- **Building generation in a plot/Building parameter modification:** When generating or modifying a building in an intervention plot is needed, the user can use this function for building transformation. Several parameters, such as building height and offset distance, can be managed. Except for the indicators that are analyzed and induced by the analysis modules, the attributes of the urban entities can be changed, as summarized in Table 13.

Table 13 Attributes of urban entities

Entities	Attributes (Unit)	Notation
Site	Site area (m^2)	A_{site}
	Buildable area (m^2)	$A_{buildable}$
	Number of households (N)	N_{house}
	Maximum allowed gross floor area (m^2)	$maxA_{GF}$
	Gross floor area (m^2): $A_{footprint} \times N_{floors}$	A_{GF}
	Maximum allowed footprint area ratio: Coverage ratio ($\%$)	$maxR_{footprint}$
Building	Floor height (m)	H_{floor}
	Building footprint: Ground floor area (m^2)	$A_{footprint}$
	Coverage areas (m^2)	$A_{Coverage}$
	Maximum building height (m)	$maxH_{building}$
	Maximum number of building floors (N)	$maxN_{floors}$
	Number of building floors (N)	N_{floors}
	Building usage ($String$): Residential, Office, Commercial, etc.	$U_{building}$
Network	Number of junctions (N)	$N_{junctions}$
	Road and street areas (m^2)	A_{road}
	Length of road/street segment (m)	$L_{roadSeg}$
	The width of the road/street segment (m)	$W_{roadSeg}$
External space	The area of public space (m^2)	A_{public}
	The area of private space (m^2)	$A_{private}$
	The area of parking space (m^2)	$A_{parking}$
	The area of green space (m^2)	A_{green}
	The area of the water body (m^2)	A_{water}

- **Street addition/Public space insertion:** By using the axis(s) as an input, a new street segment with a specific width is generated. Under the "Street addition" mode, the number of lanes and the width of each lane can be modified but only limited to minor modifications in order to focus on the conceptual design of the urban masterplan. Under the "Public space insertion" mode, the usage attribute of the selected block that is enclosed by axis lines is changed to “public space.” After that, the building volume generation is limited; for example, a block that is used as a public space is not considered a buildable area.

3.4.2 Urban Variants Synthesis Methods

The synthesis methods of urban variants are composed of several procedures by adapting user inputs and several geometries transformation operations. Inputs to construct a basic data structure of the urban entities are the axis lines representing either the endpoints of roads or streets network. A collection of axis lines can be manually given in the drawing window frame of the design support prototype or imported from file data. When all axis lines are loaded, intersections among axis lines are found step by step from the left to the right and the bottom to the top order. If a selected axis line has n respective intersection points (i.e., nodes) between two endpoints, $n + 1$ line segments (i.e., links) can be made by connecting two neighboring points of the axis line. If no line segment is found on a selected line, this selected line is not considered for use in constructing the network data model because it is not linked to other axis lines, therefore leaving it frozen. After the execution of the line-line intersection algorithm, a set of nodes and links are obtained, which are used as inputs for constructing the base HEDS.

In the design support prototype, firstly, axis lines representing road networks and polygons representing the boundaries of the intervention site are required to generate an initial urban pattern. Through the design process, the designer can modify the axis lines via the graphical user interface (i.e., GUI) directly. All intersection points among the axis lines and the bounding polygon are found, which is used to generate enclosed polygonal areas that possibly represent blocks in the later steps. For the generation of the blocks, the axis networks that are composed of the line segments and the intersection points are parsed into a half-edge data structure, which is composed of three entities such as vertices, edges, and faces. In this half-edge data structure, the generated faces are transformed into their geometric representation as polygons. When representing urban entities, it is identified that the use of the half-edge data structure has several advantages.

In the case of representing blocks and districts of an intervention site, the half-edge data structure can provide several functions to be used for controlling urban entities and supporting user interactions, such as i) When the designer selects a particular axis line, its adjacent axis lines can be referenced. ii) When a block is selected, her incident (neighboring) blocks can be pointed. iii) As a road segment is positioned between its incident blocks, two confronting perimeter blocks that are divided by an axis line can be referenced by selecting the road segment. iv) Blocks that meet at an intersection of axis lines can be referenced by querying edges, of which end is the intersection of the blocks. v) It is simple to manage road segments that surround a particular block. Figure 26 shows a pictorial representation of the basic pointers used in the urban structure model using HDS. The center block in the left image of Figure 26 has four pointers to its neighboring blocks. Each block is modeled based on HDS, which enables managing high-level geometric operations, as introduced in Subsection 3.4.1.

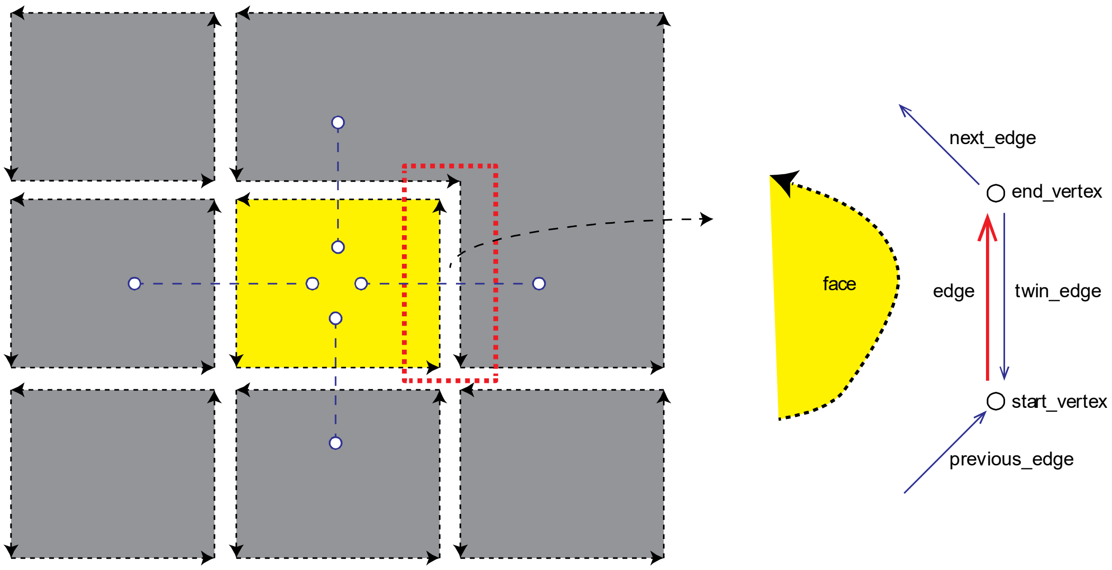

Figure 26 The basic pointers used in the urban structure model using HEDS

Secondly, a designer can navigate blocks to generate different layout typologies. Rules to generate different block layout styles are adapted and developed, with which the designer can replace the initial block with variations of perimeter block style, for example, i) by using a simple buffer algorithm for the synthesis of perimeter block typology or ii) by using subdivision method for the partitioning of a block region into small plots. Therefore, different subdivision approaches can be applied, depending on the designer's preferred block layout style, corresponding to the intervention block's required function.

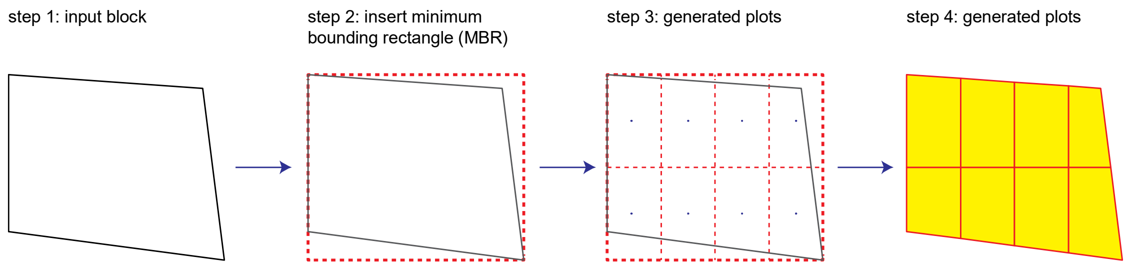

Figure 27 An example of the application of the subdivision method to a convex block

Figure 27 shows an example of the application of the subdivision method to a convex-shaped block to allocate smaller plots in a selected block. In this example, a minimum bounding rectangle (MBR) of the chosen block is calculated, and then temporal dividing lines are overlaid in the MBR by using the given minimum and maximum size of a plot. Finally, overlapping areas between the original block's polygon and the dividing lines are calculated to generate smaller plots inside the block.

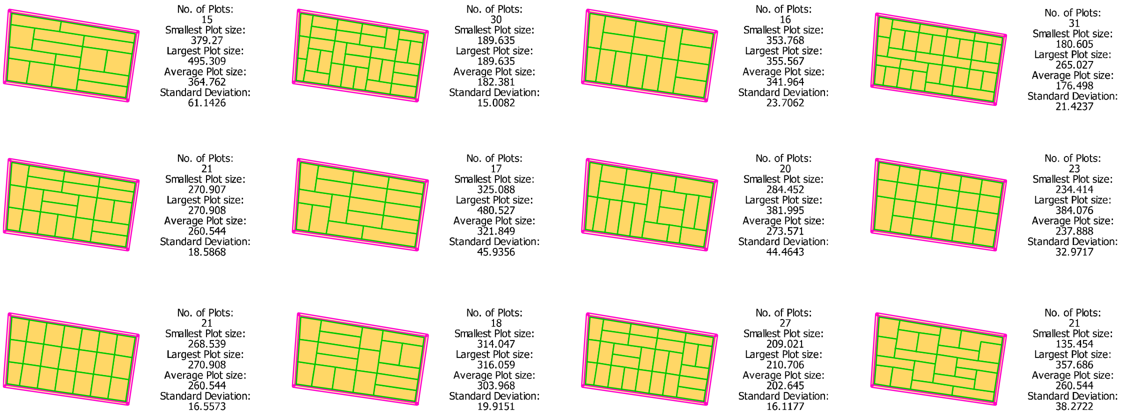

Figure 28 Plot allocations using the block subdivision algorithm for the gridiron system typology

Figure 28 shows design variations of a convex-shaped block by applying the subdivision algorithm. This method can also be used for dividing a block into smaller blocks and for a non-rectangular boundary. Figure 29 exemplifies the application of a subdivision method to a non-convex block to allocate smaller infill plots. A difference is that if the working block boundary is not a convex polygon, it is decomposed into a minimum number of convex polygons. The rest of the process for the plot allotment follows the subdivision method depicted in Figure 27.

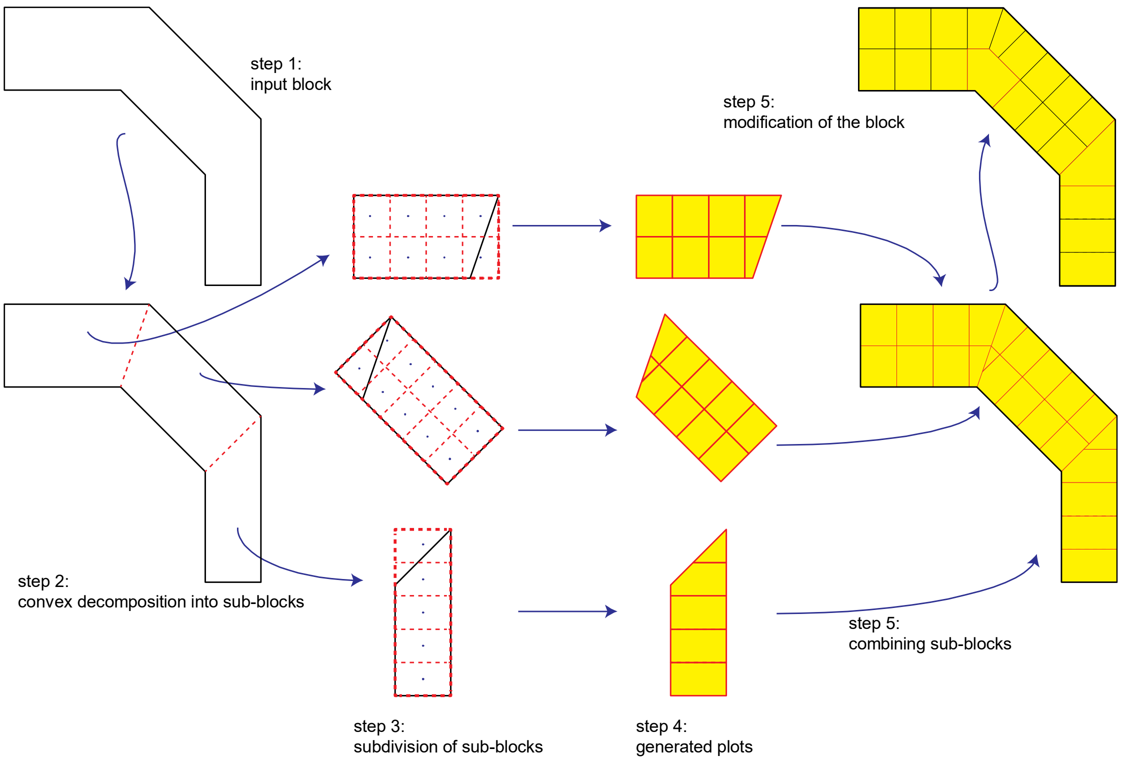

Figure 29 An example of the application of a subdivision method to a non-convex block

If the size of a plot is smaller than the pre-defined minimum site of the plot or if other plots surround the plot, it can be merged into their neighboring plots. In this manner, the generation of tiny plots can be avoided, and more diverse layouts can be tested.

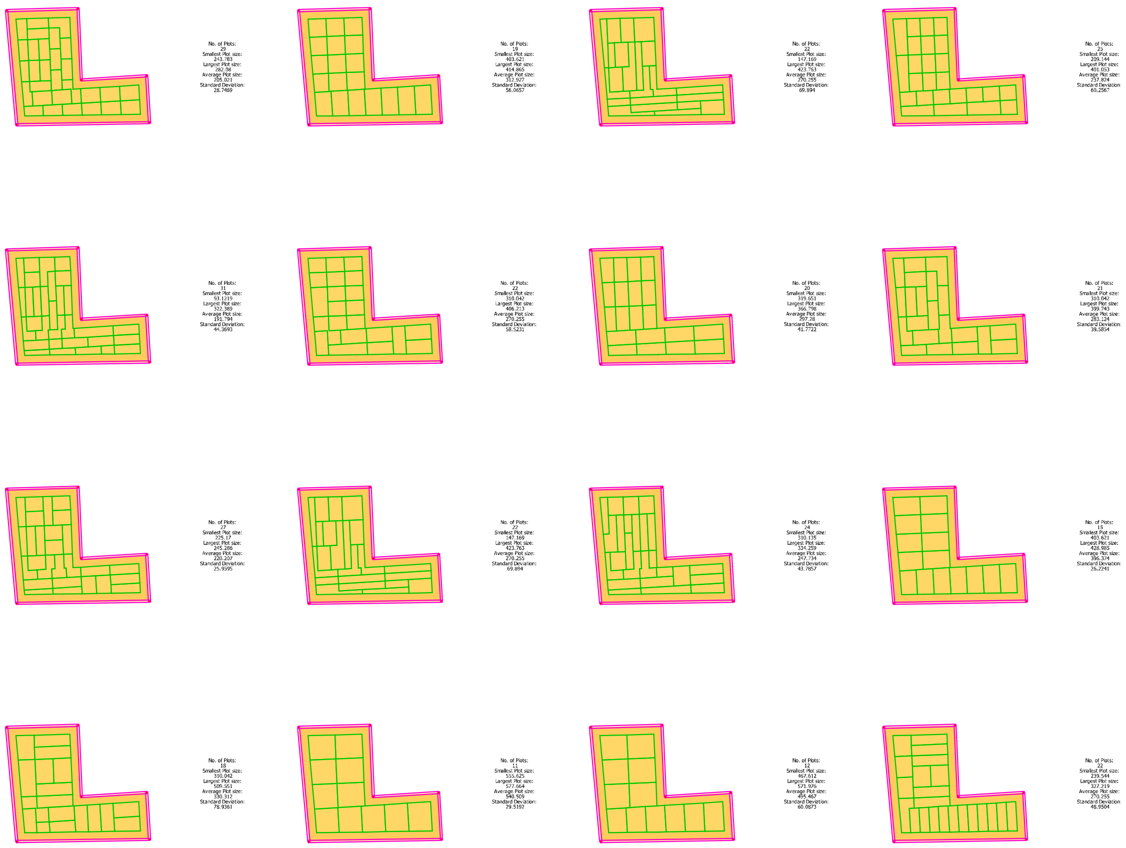

Figure 30 Design variants using block subdivision in L-shaped block

Figure 30 and Figure 31 show examples of design variants of non-convex blocks, respectively. Another method for decomposing the non-convex blocks is used in this case, which is unlikely to the decomposition method in Figure 29, which may generate plots with acute angles (see: Step 4 of Figure 29). Instead of making a new line segment that connects existing vertices on a block's boundary, a new vertex is inserted on a boundary line segment. As a result, a line segment is inserted between this vertex and a relevant reflex vertex (Schneider and Eberly, 2002, p. 770). Different decomposition approaches for the subdivision of the non-convex blocks are tested, and I find the method using a vertex insertion on a line segment more appropriate for obtaining plots with less acute angles. In addition, by controlling the minimum size of a plot and the level of randomness, it is possible to generate diverse block layout configurations.

Typically, multiple plots are synthesized from the decomposition of a block, but if the typology of the block is an enclosed perimeter, then the intervention block is dealt with as a unitary plot rather than multiple smaller ones. The enclosed perimeter block's unique characteristics are that its inner courtyard forms open space, which is encircled by buildings. In order to represent building volumes and the open space from the perimeter block, two offset polygons have to be defined; the one is the outer polygon that meets road networks, and the other is the inner polygon that surrounds the inner court. These two polygons are used to delineate a possible area for placing the building layout, which is represented by using the HEDS as well.

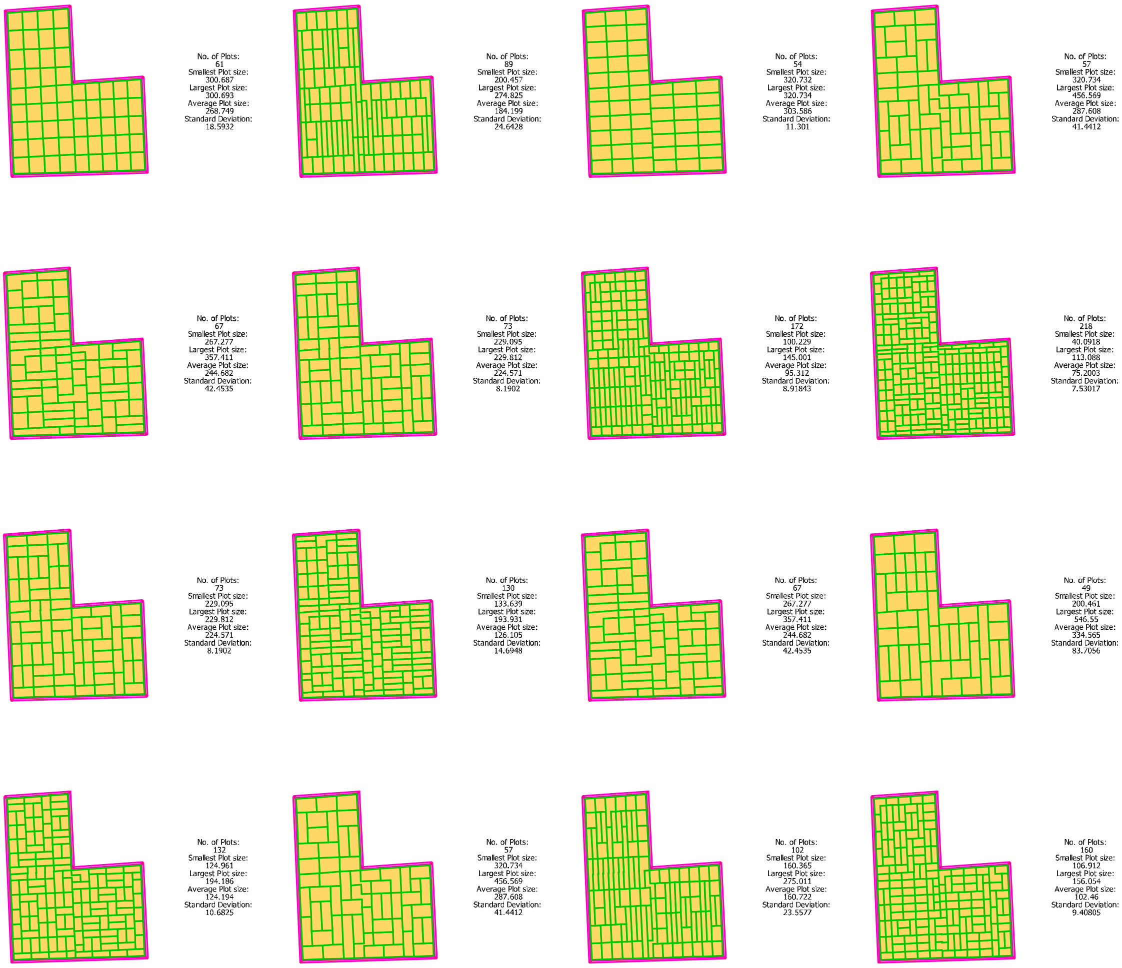

Figure 31 Design variants generation in L-shaped block using block subdivision algorithm

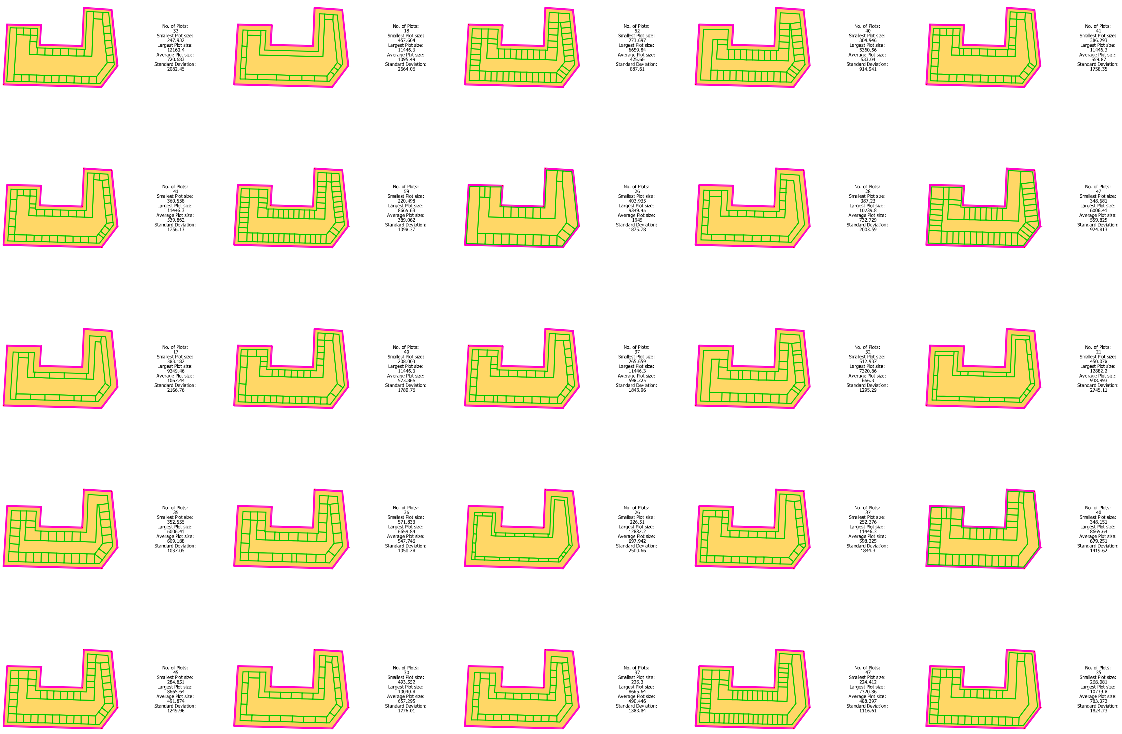

Figure 32 Design variants of perimeter block housing of U-shaped block

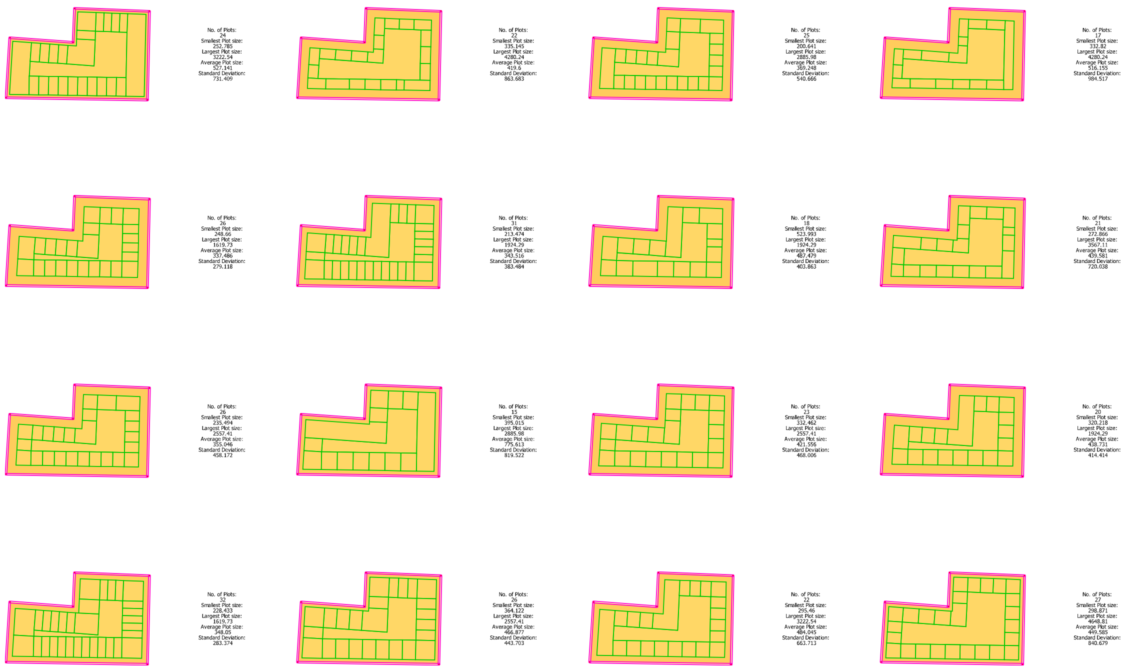

Figure 33 Examples of design variants generation using a perimeter block housing algorithm

Figure 32 and Figure 33 show the design variations of the perimeter block housing typology with different block boundary shapes. Another idea to generate this kind of perimeter block housing typology is by using the subdivision method that is introduced in Figure 27 and Figure 29 and uses the generated plots for generating buildings that surround the block. The data structure supports checking a condition if a plot meets its incident road network; therefore, the modeling of buildings that face outwards and inwards the working block is possible.

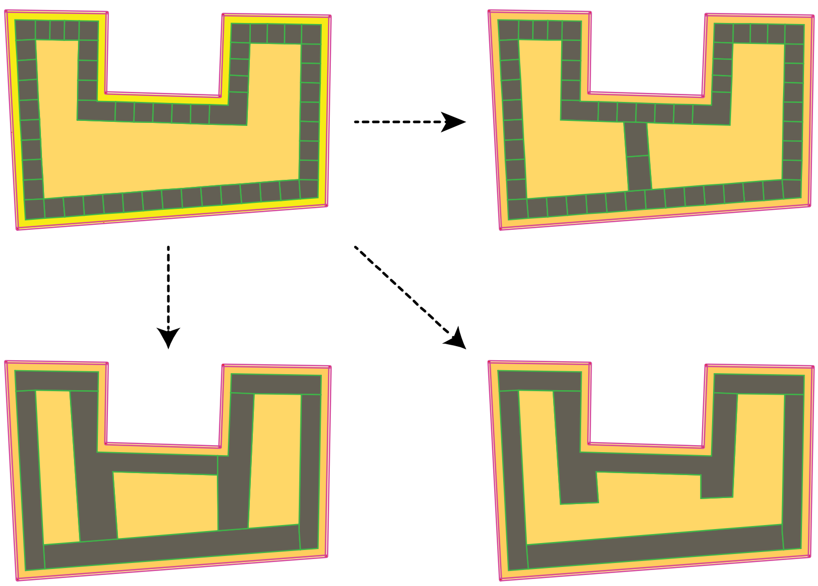

Figure 34 Examples of transformations for diverse block layout configurations

However, instead of using the generated block variants without further modifications, the proposed method is flexible in that the designer can transform them interactively by using “Plot

Division" and "Plot Merge" operations. If the designer is not given the capability to freely transform the urban entities freely, it will be difficult to avoid urban fabric's uniformity in some cases and achieve a promising design concept. For example, one of the generated block variations can be used as a final block fabric, or it can be used as a template for developing more ideas, as shown in Figure 34. In this method, it is possible to support the operation that designers commonly have used for developing urban design ideas, i.e., relating parts to a larger whole, as discussed in Subsection 2.3.1. Therefore, depending on the designer's preference, it is possible to generate unique urban configurations, as discussed in Subsection 2.3.2.

Each building knows its incident buildings with the use of the HEDS, and it is possible to design buildings while managing the topological relations between buildings automatically. For example, the human designer can divide a building footprint into several units or merge several building footprints into a single unit the other way around. Besides, if a half-enclosed perimeter block style is intended, a specific portion of continuous building footprints in a block can be deleted in order to make the block more opened. More radically, generating several courtyards instead of a unitary one is supported by inserting building rows fitting into the inner area. Figure 35 shows two building configuration examples on the same plot layout of the gridiron system typology.

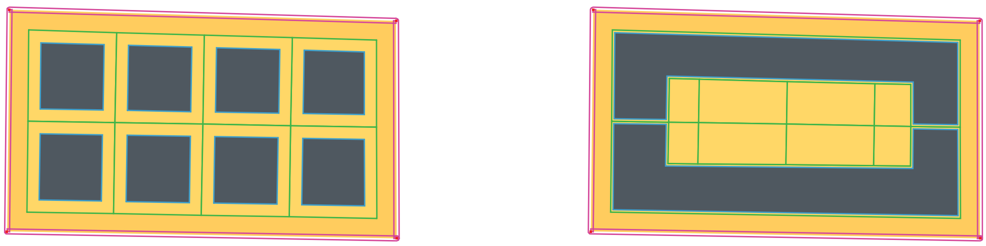

Figure 35 Examples of building configuration on the identical plot layout

When the designer intends to generate more design variants of a block, which are different from the current working design, the design support can automatically generate design variants based on pre-defined rules. These generated design variants are visualized in an independent widget and kept as alternatives of the working block to navigate them interactively. By visualizing multiple design layouts in conjunction with each variant's evaluation data, the designer can compare them intuitively and make a more informed decision.

Lastly, the urban design support has design history management, allowing the designer to navigate different design sessions and reuse specific design sessions' urban design ideas to develop design concepts further. This computational urban design support is explained in the next chapter.

4 Interactive Exploration of Urban Design

In Chapter 3, the overall functions of the proposed urban design support, which aims at supporting designers, are explained. In this regard, the design support prototype can provide design assistance for the routine problem-solving activity, e.g., with automatic layout design algorithms and more creative design assistances with semi-automatic methods. The research focus is not only on the realization of functional requirements of the urban design support but on how the developed methodology can be used as intended in order to stimulate the design activity. Therefore, in Chapter 4, relevant research questions need to be answered, such as:

- *How can the naturalistic design behavior be supported by the design support* prototype*?*
- *How can the explorative activities in which designers co-evolve the design problem and solution be improved by the design support?*
- *How can the generative design support increase explorative opportunities to the design generation path?*

Rather than these questions are discernable exclusively, these questions share common aspects of what kinds of design support can be provided to improve design activity. For addressing these questions, the theoretical background in relation to these questions was presented in Section 2.1, which helps justify the interactive function of the design support, as depicted in Figure 36.

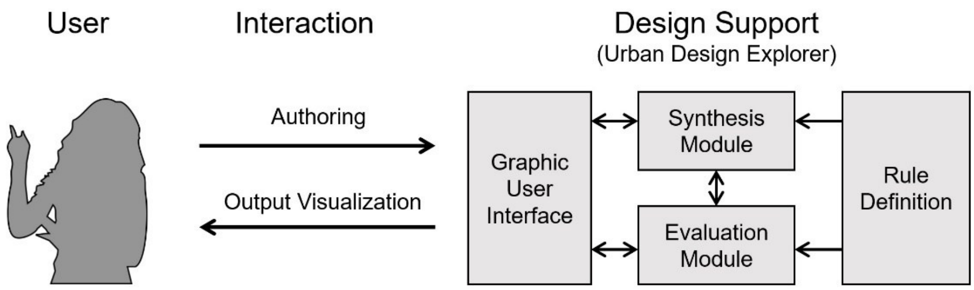

Figure 36 The overview of the interactive exploration of urban space design

4.1 Design Exploration Support

With the advance of CAD tools, as discussed in Section 2.4, many design tasks have been automated; however, it is admitted that human intervention is indispensable in the development of more creative ideas and concepts (Chakrabarti *et al.*, 2005; Horváth, 2005). In particular, it is requested that CAD tools should be designed to support the designer's cognitive activities (Ullman, Dietterich, and Stauffer, 1988), such as for supporting the co-evolution of the design process (Maher and Poon, 1996; Maher, Poon, and Boulanger, 1996). From this perspective, design supports should be advanced, which can improve idea exploration and improving interaction with the human designer during activities for design synthesis.

Even if those findings in Subsection 2.1.5 are mostly based on the sketch-based design task experiments, some implications should be considered in the development of the design support. As can be informed from the discussion of the convergent and divergent in design creativity, many researchers subscribe to the view that frequent shifts between divergent and convergent thinking are necessary for creative design. The focus then moves onto how the design support enables for managing design activity, which helps manage frequent shifts between divergent and convergent thinking. From this perspective, the following Subsection proposes what kinds of utilities should be supported while human designers generate ideas during the urban design process. Two design supports for interactive urban design exploration are proposed[8], such as:

- To suggest multiple alternatives for a particular urban design problem.
- To manage the design history, which enables backward-tracking and side-tracking of design states.

The first design support's premise is that if designers are provided with these alternatives[9] and supported to explore them at different levels of detail, they can increase their chances of developing promising ideas. The second design support's premise is that if human designers can navigate and reuse design states, they can be assisted in shifting efficiently between divergent and convergent thinking. I will further discuss these premises as follows. The difficulty that human designers have faced are two-folds. In practice, designers often consider design concepts based on a few ideas and thereby are limited in generating a number of possibilities. It is assumed to be a good design approach if designers are supported to generate the broadest possible range of ideas and then explore them. The current computational design support approaches

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[8] I consider these two functions are necessary for supporting human designers' naturalistic design activity. The generative design methods that are discussed in Section 2.4 are ample but not flexible enough for human designers to develop their ideas actively. This research's concept of suggesting multiple alternatives is to increase the opportunity to develop the human designers' own ideas based on what is suggested rather than to select one. Also, effective use of design history, which is not supported in the generative design method, can enhance the flexible design activity. These design supports will be tested through a design experiment in Chapters 6 and 7.

[9] The terms, i.e., variant and alternative, are used interchangeably in design research, but there are subtle differences in meaning. According to the Oxford Dictionary, the alternative is defined as "*one of two or more available possibilities*" and variant as "*a form or version of something that differs in some respect from other forms of the same thing or from a standard*." In generating design solutions, if designers were generating numerous slightly different solutions related to a specific problem, it may be considered solution variants rather than solution alternatives. On the other hand, if designers generate substantially different solutions that are influenced by a different interpretation of requirements or "*a shift of frame*" (Akin and Akin, 1996; Schön, 1984), the solutions may be considered as alternatives.

pertinent to the generation of urban design, as summarized in Chapter 2, lack adequate support for multiple design alternatives in parallel. Moreover, the direct transformation on the design development remains limited in the case of using automated approaches. When designers are given the flexibility of alternating design ideas' parameters, it is possible to generate different alternatives for design problems in which the human designer is involved.

Moreover, the use of a parametric approach can allow for densely ordered states or overlapping states of solution space, which were assumed by Goel as a necessary condition for inducing lateral transformation. This approach can allow human designers to remain non-committal about the state in which they are. In short, it allows designers to compare different options without spending opportunity costs effectively. As a result, this might facilitate divergent thinking and, therefore, the exploration of alternative solutions.

Also, not to mention a wide range of sources from outside, the reuse of the designers' own design ideas that are considered throughout the design process is beneficial, which is not well supported in current CAD tools. For example, the design ideas generated in the past of the design process have become frequently a valuable source of inspiration. Moreover, designers use prior ideas to evaluate the new working ideas, or they can transform past ideas that were judged infeasible into good ones, for example, by patching a partial solution as discussed in Subsection 2.1.3.

However, remembering or recalling design ideas without efficient, systematic management is a cognitively demanding task. If the number of design alternatives to a problem continues to grow, it becomes impossible for human designers to consider them meaningfully. Such a situation can be improved if designers can flexibly navigate design states using computers, in which a wide variety of design ideas are considered. Therefore, the design support that can manage the design history by enabling backward-tracking and side-tracking of design states is proposed. The current CAD tools have corresponding operations such as "Undo/Redo," but these do not mean that keeping multiple idea developments is supported. More importantly, the management of design history is automated in the proposed design support prototype, which enables to unburden designers' cognitive overload. By allowing human designers to navigate and reuse the design states in design history, designers can develop further new ideas by evaluating and modifying previous design solutions. Through this approach, I assume that designers can be assisted in shifting between divergent and convergent thinking frequently.

Some effects of the interactive generation of design alternatives are predicted as follows:

- Firstly, human designers' cognitive activity can be more stimulated through interaction with the proposed design support. For example, if an individual experiences short-term design fixation, which stagnates or hinders the search activity, the interaction with the design support can make the urban design more active by arguably allowing the search for unexplored new problem and solution areas.

- Secondly, the designers may be likely to concentrate on more creative activities instead of spending time and effort on routine design tasks. Specific design sub-problems that are formulable are implemented for the automated design generation and analysis tasks in the design support. For this, parametric rules for the block layout generation are formulated based on urban typologies considered. In addition, various evaluation methods are combined into the design support, as discussed in Section 3.3. As a result, the integrated approach for form generation and analysis may help unburden the designer's intensive cognitive workload.
- Thirdly, premature design alternatives, which might be turned out infeasible in the later design stage, can be screened out in advance through the proposed design support. If that is the case, the design support can be used to reduce the opportunity cost. Of course, abandoning unique design ideas without enough examination must be avoided, and infeasible ideas can be improved by merely "patching" activity, as discussed in Subsection 2.1.3. However, possessing many design alternatives to the degree of exceeding the designer's capacity will impose an unnecessary strain on the designer's cognitive workload.
- Fourthly, decision-making can be influenced by how design alternatives are presented to the user. The design support can generate various design layouts using parameterized rules. Rather than presenting design alternatives one at a time, showing several design alternatives to the individuals can simultaneously help them make more optimal decisions (Basu and Savani, 2017).

4.2 Human-Tool Interaction Support in Urban Design

I will further explain how the urban design support prototype can support multi-level successive design activities through the concept of a "design search cycle" model between a user and the urban design support. During the conceptual stage of urban design, 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, gathering information, and generating design solutions for the identified design problems. Any design task has a start and an end. According to Lawson (2006), different strategies can be adapted or adopted concerning problem formulation and solution generation. As shown in Table 14, the problem space and solution space can be mapped to different design models, such as Oxman's ICF model (Oxman, 1994; Oxman, 2001) or Gero's FBS model (Gero and Kannengiesser, 2004; Kelly and Gero, 2015).

These models are developed to be used in different contexts, but they can be used to describe the evolving design development.

Table 14 Mapping of problem and solution spaces onto Oxman's and Gero's design model

	Oxman's ICF model	Gero's FBS model
Design problem	Issue	Requirement Function Expected Behavior
Design solution	Concept Form	Actual Behavior Structure

The evolution of ideas is a vital element in design while utilizing the proposed design support, by which, continuously inspired by multiple perspectives, human designers generate possible new solutions and represent the ideas. So, the ideas are managed in the form of external representation. Moreover, the design is an iterative cognitive process of idea generation, representation, and evaluation (Jin and Chusilp, 2006), which can be graphically represented as the case of a tree network by Kavakli and Gero (2002, p. 39). The design states can be described as a tree network, where the design outcomes are results evolved from design states. While exploring design space, the proposed design support can track the representation of designers' thoughts at a specific time as a tree network, aiming at recording every idea generated. It can record the entire design process as a directed graph of design sessions[10]. In relation to storing the design process: it stimulates the use of earlier ideas in the idea generation process by enhancing their accessibility. The design support could be valuable in exploring design alternatives, possibly allowing access to new exploration paths to human designers fluidly. Such an approach could enhance human designers' creative processes by exposing them to new opportunities for exploration. Current urban design tools do not readily afford the mechanisms which are proposed in this research.

4.2.1 The Concept of Problem and Solution Search in Urban Design

Urban design is to be completed when a solution to all the urban problems arrives at an acceptable or satisfactory level of degree. The urban problems can mostly include any means, requirement, issue, value, or context that demands a response/solution for an urban masterplan

[10] Technically, the detection of user's intentions based on the kinds of user activities/interaction (e.g., whether the user's activity is adding details on blocks and plots, transforming the configuration of blocks, or changing parameters of urban entities) may increase the semantics of directed graph of design sessions. When the graph becomes more extensive during the design process, it can be represented concisely by merging relevant design episodes in a way that the transformed representation does not limit the natural flow of the design. The concise representation can increase the legibility of the graph representation by adding annotations. This research concept is put as a follow-up study.

to be successful. The design problems are evoked from a different source of origin. For example, the urban designer can identify them while analyzing the facts of the intervention area, or new design problems are serendipitously discovered while developing design solutions to the previous design problem. Also, the problem conceived may evoke another design problem(s) that conflicts with each other.

For example, “access to public transportation” is quite often considered a significant issue in sustainable urban design. Whether this issue is given as a design requirement or considered necessary by the urban designer — once the issue is perceived as one of the fundamental design problems — the urban designer performs analysis of the issue and synthesizes a proper solution in response to the issue. The design problem, “the access to public transportation,” can evoke relatively related design problems, i.e., “open space design regarding location and size,” or “efficient land-use & space.” These problems are analyzed, and urban entities with a particular formal solution are synthesized and evaluated.

Designers do not always elicit only one specific solution to each design problem during the early design stage. Instead, they synthesize and test multiple solutions until they accept one satisficing solution as a final solution. If an urban designer proposes a solution to a specific problem, it is often the case when a designer retrieves a typological concept from successful design precedents, something from their own experience or memory. In such a case, designers apply analogical thinking to transform the retrieved design solution suitable to the context given. For example, after identifying the design problem such as “access to open space,” designers may synthesize a typical urban structure such as “the block typology composed of perimeter housings, which encloses an inner-courtyard in the center of the block” or any other design alternatives. These urban design solutions can often be kept as a form of external memory for a long time, and they are compared with one after the other. Alternatively, the comparison is sometimes put on hold when only one of them is decided to be developed further, or all of them are eventually discarded if the designer decides to develop a new concept.

4.2.2 Urban Design Episodes

Based on the conceptual description of problem and solution search in urban design in Subsection 4.2.1, I can provide a process model representing the problem and solution searches in urban design. When a design session is referred to as the period between the beginning and the end of an entire urban design process, the design session is supposed to consist of multiple problem searches and their corresponding solution searches, as shown in Figure 37.

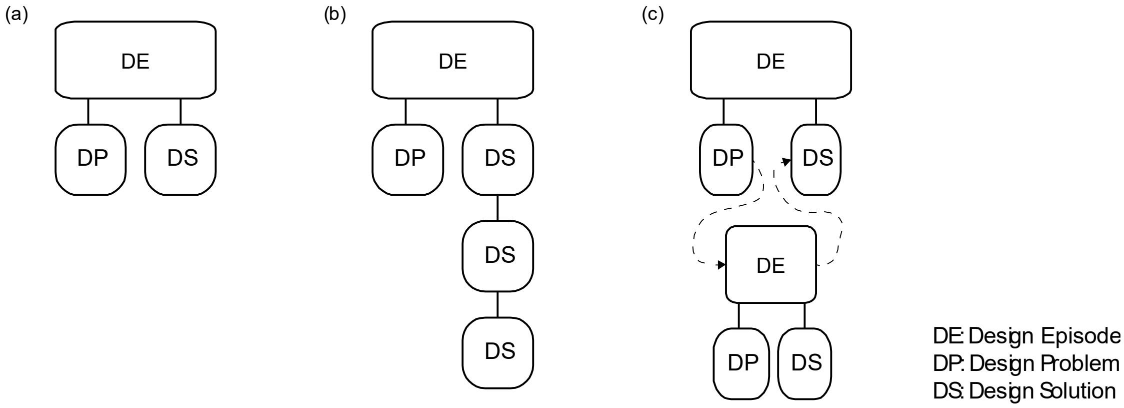


Figure 37 Cases of various forms of design episodes

Goldschmidt and Weil (1998) identified that the design session consists of multiple design episodes[11], each of which can simply be represented as a pair of one design problem search and the related design solution search, as shown in Figure 37 (a). As explained in 4.2.1, a design episode consists of designers' various activities, such as bringing up a design problem and synthesizing a design solution to address the problem. In many cases, instead of pursuing a single solution, multiple design solutions corresponding to a specific design problem can evolve concurrently, as shown in Figure 37 (b).

However, it does not occur that the human designers engage in more than one design episode simultaneously. Instead, designers prioritize a specific design problem at a certain point; the solution searches for other design problems are put on hold while they are not revisited. In such a case, the other design problems inactivated can be stored in human designers' internal memory or other forms of external storage such as sketches and written memos. Whether it may be evoked or activated at a specific time, a design problem can successively bring up other problems one after the other. It is called a 'design shift' when the designer moves his or her design attention across different design episodes. The design shift occurs when a design episode that is completed evokes other design problems; Figure 37 (c) shows a case of the design shift when a design problem of a design episode evokes other sub-problem(s). Besides, the design shift can happen in different forms, such as when a design episode is terminated after dealing with a particular design problem only without synthesizing a corresponding design solution.

[11] The analysis of the design episode has been used diversely. For example, Jin and Benami (2010) analyzed design episodes from a cognitive experiment to study creative patterns and stimulating relationships. Gero and Mc Neill (1998) proposed a scheme for analyzing design episodes to investigate the process of designing. Wiltschnig, Christensen, and Ball (2013) identified co-evolution episodes in collaborative, team-based design practice occurred regularly, which links with creative activities.

Figure 38 shows an example of evolving design episodes during a design session, where DE denotes a design episode; DE<k> denotes k-th design episode; DP is a design problem; DS is a design solution. The shifts of design focus across different design moves are portrayed in a graphical representation, “Linkography” in Goldschmidt and Tatsa (2005).

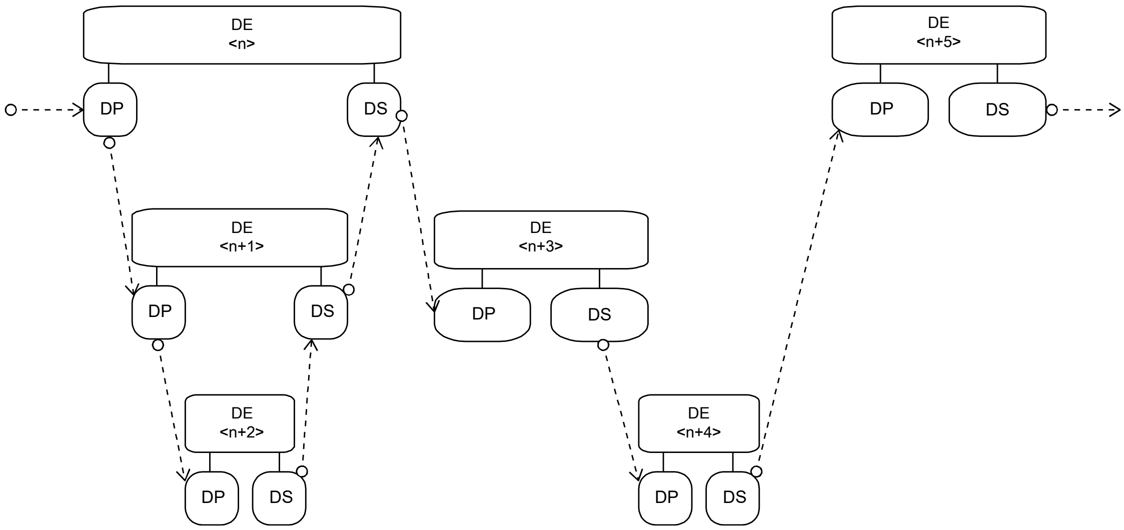


Figure 38 A conceptual representation of evolving design episodes during a design session

Concerning the order of priority between the problem search and solution search, a question can be raised. This is because the example above shows that the design problems precede design solutions. *Does the problem search always precede the solution search?* Of course not. It may be possible for a designer to synthesize form and space without identifying the corresponding design problem, but they are coupled in the following stage if the form and space become meaningful. In particular, this kind of practice can be found more often in the early design stage when ‘how’ is unclear, and the desired value that designers wish to achieve is also indistinctive, as explained via abduction-II thinking in Subsection 2.3.2.

Figure 39 demonstrates an example of the design exploration using the parametric generation of urban block layouts. The block layout configurations in this design session show the design progress (i.e., from DE<n> to DE<n+4>) of layouts in four urban blocks. For example, the design idea at DE<n+1> is the first block layout that is advanced from DE<n>. Upon receiving the user's operation command, the design support generates different urban layouts for the intervention area. Several block alternatives, based on the gridiron system typology, are generated and adapted for each block, and the final layout configuration is reached at DE<n+4>, with which the design idea can be explored effectively, and the designer can compare ideas for making a more informed decision.

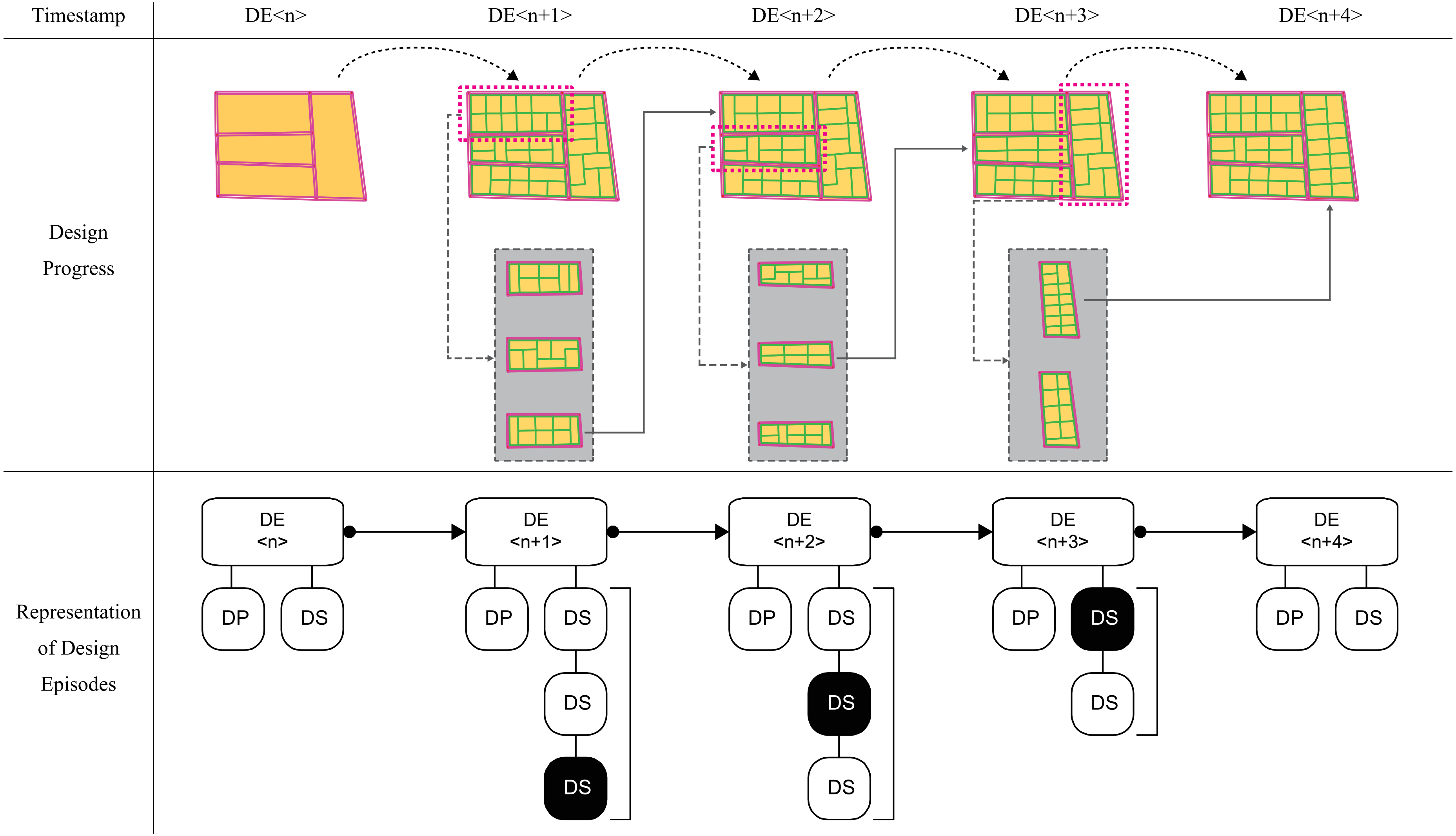


Figure 39 An example of the design exploration using the parametric generation of block fabrics

4.2.3 Design Episodes Exploration

The concept of an interactive model between human designers and the design support is introduced to represent the 'design search cycle.' It is based on the conception of the design process as an iterative or recursive search process (Suwa and Tversky, 1997) or self-reflective practice in which designers think in action (Schön, 1983). Also, the essential features for an interactive layout design method are suggested in Section 2.5, among which *adaptability* denotes that the design support is flexible for new problem formulation when an unknown problem situation is discovered, and *circularity* means the iterative solution-problem co-evolution. Such interaction in the design support can be represented as in Figure 40.

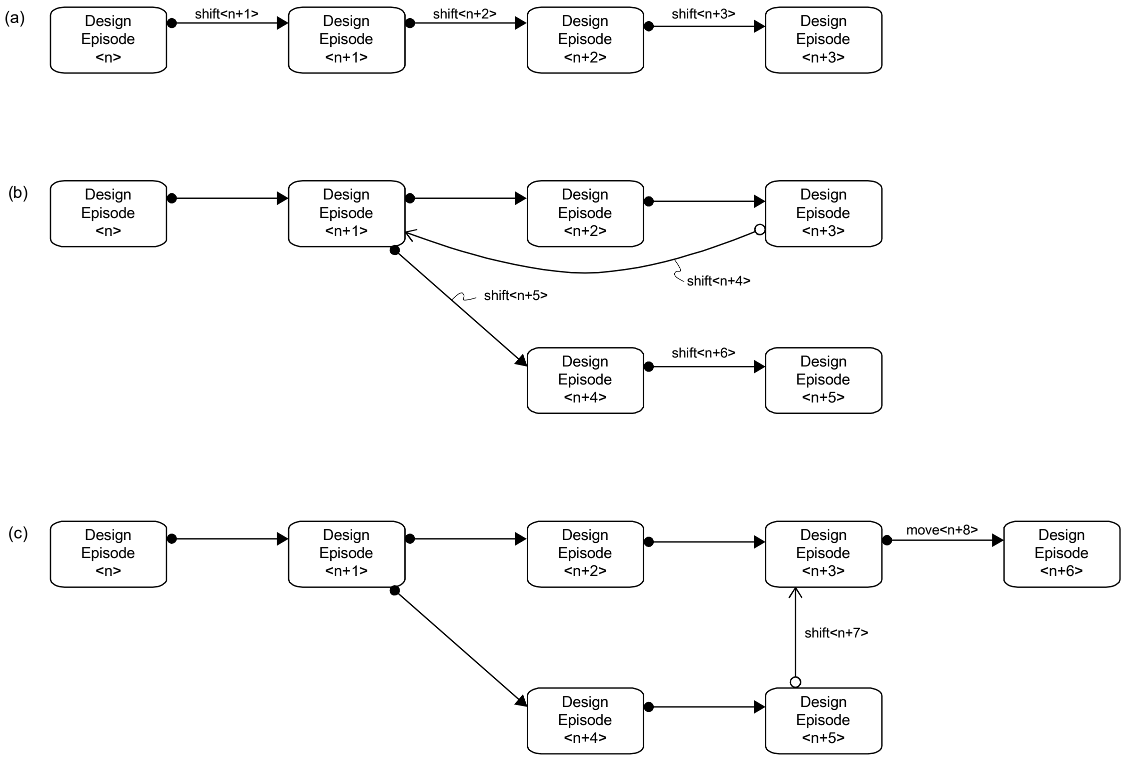


Figure 40 Exploration of design ideas using the navigation of design episodes

Figure 40 represents an example of the navigation of design episodes in a design session, where Design Episode<k> denotes the k-th design episode, and shift<k> is the k-th design shift. While Figure 38 shows a design development in a linear form, which relies on the continuous making of a new design idea, Figure 40 is the case that previous design episodes are referenced to explore a new idea. Figure 40(a) is a case of gradual design development in a linear form, from the n-th design episode to the (n+3)-th design episode. In Figure 40(b), through the (n+4)-th design shift from the (n+3)-th design episode, the human designer can recall the (n+1)-th design episode. I call this navigation backtracking since the (n+3)-th design episode is subordinate to the (n+1)-th design episode. Subsequently, the human designer proceeds to the (n+4)-th design episode from the (n+1)-th design episode, and the (n+5)-th design episode is followed.

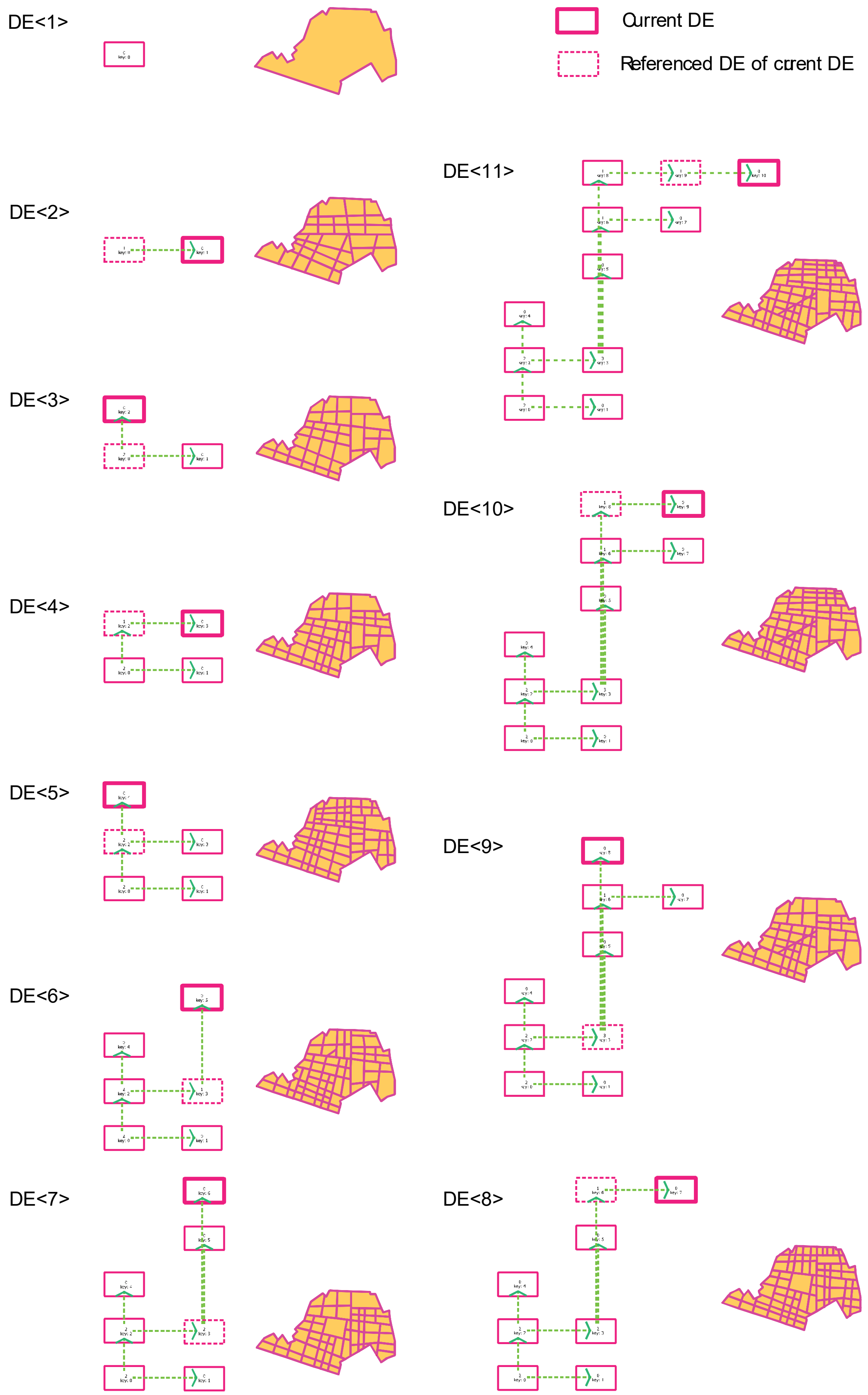


Figure 41 Exploration of design ideas for the site layout using design episodes navigation

Human designs can navigate the design episodes that are previously visited but not dependent on. In Figure 40(c), through the (n+7)-th design shift from the (n+5)-th design episode, the human designer can recall the (n+3)-th design episode. Unlike backtrackings, I call this navigation sidetracking since the (n+5)-th design episode is not subordinate to the (n+3)-th design episode.

Figure 41 shows an example of design ideas exploration for the site layout design using the design episodes navigation in the urban design support prototype. In this example, a total of eleven design episodes (i.e., sequentially from DE<1> to DE<11>) are included to demonstrate the idea development for the site layout. The site layout at design episode 1 (i.e., DE<1>) is the original layout without any information except the site's boundary. At DE<2>, the initial transportation network is overlaid by considering nearby roads, orientation, and access points. While holding the idea at DE<2>, a different idea is introduced at DE<3>, and which is further developed at DE<4>. This kind of application of different navigation methods is used until reaching the final site layout at DE<11>. Through the use of design history navigation, the designer can test different levels of design ideas flexibly. In particular, the interactive use of backtracking and sidetracking enables one to recall design ideas at other design episodes and develop further. In this manner, the designer can avoid adhering to a single idea or control the level of details, if necessary.

4.3 Interactive Urban Design Exploration

The ability to compare a current design solution with their previous ones is an essential aspect of the learning process. The work process using the urban design support can contribute to enhancing the *explorativity* (i.e., the ability to flexibly define, modify and explore a search space on different paths) and the *immediacy* (i.e., the ability to immediately see the effects of his or her actions or decisions at crucial moments). By using the input data from the user as a base, the computational urban design support recursively generates and analyses a number of design proposals. As a visual form, the generated design alternatives are suggested immediately to the urban designer.

Instead of delegating the tasks of the urban block layout generation to the design support, the user (designer) can have more control over the idea developed during the design process. When an intervention plot (block) under being designed is queried to the design support, a number of block layout alternatives are to be visualized by running the generation module of the design support. The generation of three different block typologies (i.e., Gridiron system, Perimeter block housing system, and Block tower) is implemented in the prototype. The prototype uses the plots and blocks that are incident to the selected urban entity, of which information is necessary to generate the new layout design of the intervention plot (block). The layout alternatives are the outcome of the iterative evaluation and synthesis in the design prototype. In the evaluation module, density, openness/visibility, connectivity, and sunlight are selectively evaluated at the district level[12]. For instance, only one evaluation method can be applied to different layout synthesis modules, or different evaluation methods can be applied one by one to a specific layout synthesis module.

In the synthesis module, automated form generation algorithms, as suggested in Subsection 3.4.1, are applied for layout generation. For the generation of a perimeter block volume in an urban block, for instance, a skeletal base drawing that shows areas for the building volume and the inner court is calculated and suggested into the urban block in work-in-progress. The iteration of the prototype's evaluation and synthesis operations is not intended to generate only optimal design solutions if a specific weight to each evaluation variable is not given. Preferably, it is to provide the user with more immediacy for exploring a search space on different paths.

The rules for the synthesis of urban layouts and building volumes, which are predefined separately, can be applied arbitrarily in the intervention area. A single preferred rule for the synthesis of urban layout can be used independently, but multiple different rules can be applied all at once. In this case, the solution search is conducted quickly to prevent waiting time for visualizing the temporary outcomes, which enables the user to quickly see the design alternatives calculated in the evaluation and the synthesis modules.

While the design support allows the human designers to navigate the design episodes flexibly, there is no means to recognize the transformation of design spaces at each episode automatically. So, there exists a complexity in managing design episodes. It is also challenging to avoid redundant design spaces, which can increase the number of design episodes to manage. In the later stage of the design process, for example, the number of design episodes that should be managed will increase gradually. In this case, managing them at an acceptable level must be considered. Basically, the design support can respond only to specific events during the design session. In other words, when the design support detects user events such as a form of mouse events or key events on the interface level at a specific time, design solutions on the current working design

[12] Depending on the project characteristics, these aspects are substantially considered together with dynamic simulations such as outdoor wind flow and sound propagation, if available. Particularly, Chiaradia, Sieh, and Plimmer (2017)'s research on the definition of urban design in terms of value, students that participated in the urban design studio reflected these aspects for developing their design concept proposals, however, for which any automated methods seem not to be applied.

concept can be recorded in the database and recalled for further idea exploration. However, such an automated recording of design history is not recommended during the design experiment if more precise tracking of design development based on the designers' intent is needed.

This research has determined that graph representations explicitly represent the relationship between design episodes, by which designers are more flexible in choosing to backtrack and sidetrack design episodes. By using these utilities, designers can avoid cognitively expensive tasks associated with a purely human cognition-based recalling, such as understanding and generating design spaces. Such a capability of design history navigation is advantageous when used in design idea generation because it fosters the search for alternative solutions and, as a result, avoids biased ones.

Figure 42 shows the user interface of the implemented urban design support prototype. Detailed information on the user interface of the prototype is explained as follows:

1) *Axis Transformation*: The operations which are directly related to axis transformation are: "Axis Insertion," "Axis Modification," "Axis Deletion," "All Axis Deletion," and "Axis Connect." Using these operations, the user can draw reference lines to measure the unknown dimension as well.

2) *Block Transformation*: The operation button, "Block Selection," is widely used to represent the block information and manipulate other urban entities that belong to the selected block. For the generation of block design variants and changing the block parameters, selecting a particular block is a prerequisite. Moreover, there are "Block Division" and "Block Merge" buttons, which allow the user to manipulate block entities in the Main Canvas Widget directly. By pressing the "Block Subdivision" button, the user can add plots with different typologies, such as Gridiron system, Perimeter Block Housing, and Block tower. The block parameters control the dimension and shape of the generated plots.

3) *Plot Transformation*: There are operation buttons for plot entity: "Plot Selection," "Plot Merge," "Plot Division," and "Building Generation in a Block." When the user decides to insert buildings in different plots in a selected block, the size of a plot must be larger than the minimum size that is restricted in entities settings in the Control Panel of Urban Entity Parameters.

4) *Building Transformation*: In this panel for building transformation, only two operations are implemented: "Building Generation" and "Building Deletion." The user must select a plot to use these operations, and supplementary operations are "Floors" and "Offset" distance, which is in the Control Panel of Urban Entity Parameters.

5) *Main Canvas Widget*: The user can directly manipulate urban design entities such as "Axis Insertion," "Axis Deletion," and "Merge/Division" operations in different urban entities.

6) *Canvas Widget for Design Alternatives*: Several design variations of a selected block are visualized to the user when a button "Block Variant Generation" is pressed. Both the number of variations and their level of deviation are controlled by parameters in the control panel of urban entity parameters. When the user selects one of the variants and presses the button "Block Replacement," the selected block is replaced with the chosen block variant. When the user generates block design variants, they are saved in SVG file format, which can be used to analyze the user's behavior.

7) *Canvas Widget for Design History Navigation*: A rectangular node in this widget symbolizes a design episode. When the button "Record Design Episode" is pressed, current design ideas are saved in the pre-designated file folder, and a new rectangular node is drawn on this widget. Previous design episodes can be recalled, or the user just sees and compare different design ideas by selecting nodes in this widget. Together with the order of the design history sequence, the number of offspring design ideas of nodes are visualized to the user.

8) *Control Panel of Urban Entity Parameters*: The designer can control the parameters that are related to urban entities. At a block level, a block's offset distances to the road axis, the size of plots can be set, and the operator controls a selected block's density.

9) *Control Panel of Design Episode*: This panel is used with the Canvas Widget for Design History Navigation. Here, the user can make a project folder by typing a project name. Design episodes can be saved and loaded by using "Record Design Episode" and "Recall Design Episode," respectively.

10) *Control Panel of Analysis*: There are three analyses: Visibility, Connectivity, and Daylight Analysis. However, the last one is not integrated into this study. In the case of Visibility and Connectivity analyses, the user should decide the boundary of the analysis by controlling each maximum distance, the default of which is 200 meters. The analyzed data is visualized as simple oval shapes in the intersections of the road network. In the case of Connectivity analysis, there are two options to choose from, which are "Metric Reach" and "Intersection Density," which are considered more simple and effective than other methods.

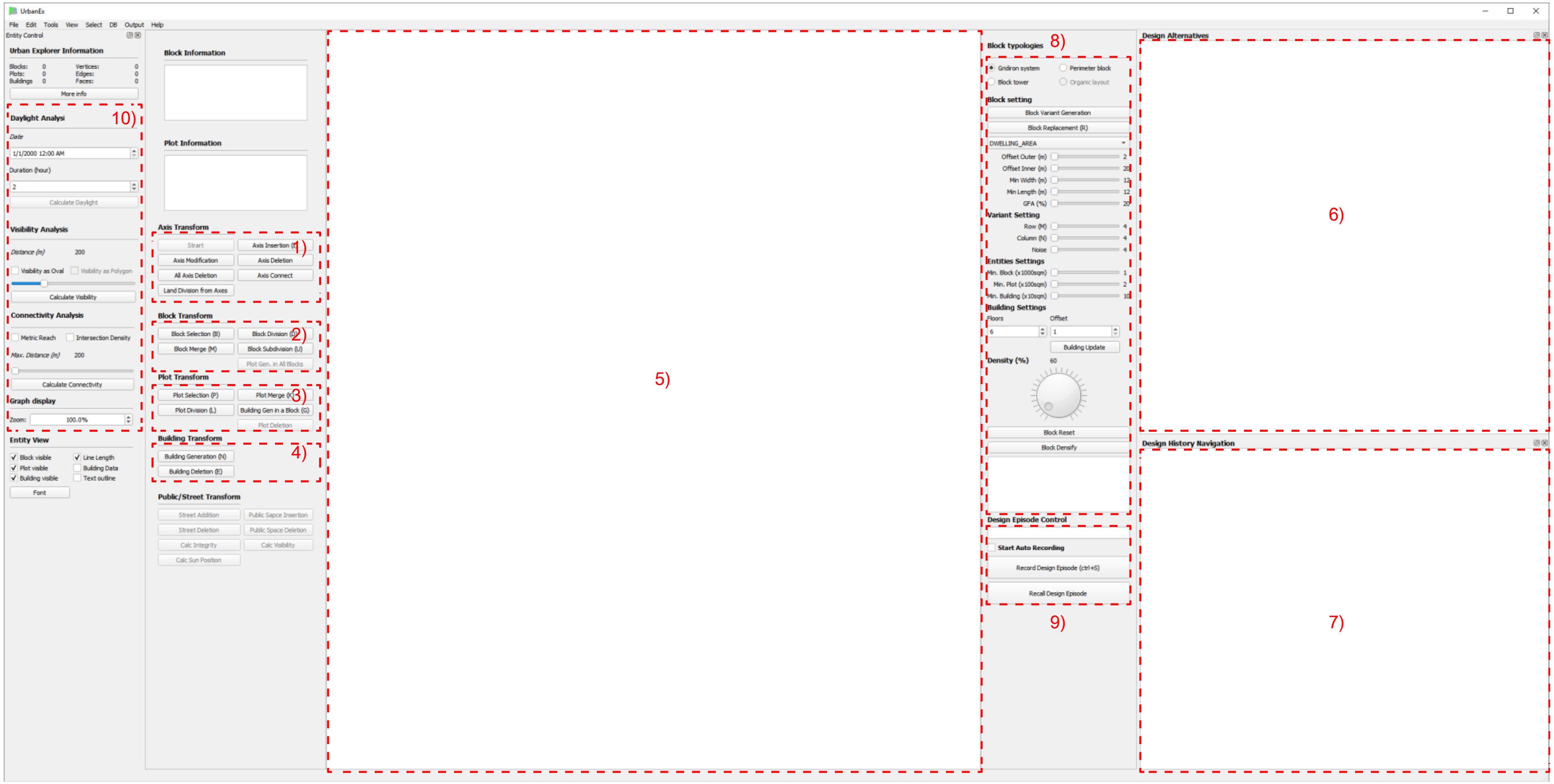


Figure 42 UI of the design support prototype for interactive exploration of urban design

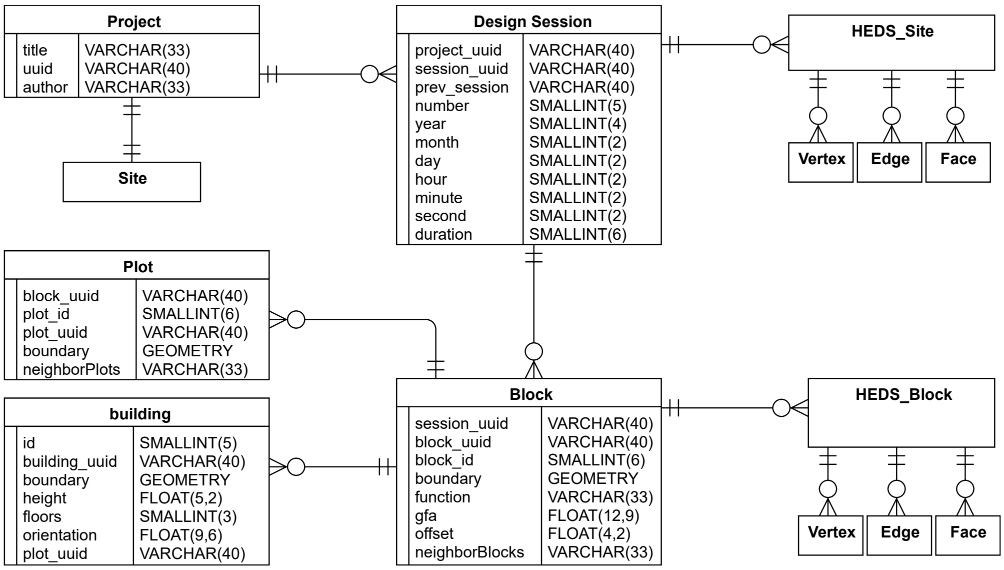


Figure 43 UML diagram for the data structure for the design history management

Figure 43 shows the data model for design history management, which is implemented in the design support prototype. This data model aims to support the control of essential geometrical and topological information among urban entities. Therefore, when a design session is recalled at a specific time, for example, the designer can use the merge and division operations without data loss, which makes the idea generation based on the recalled design efficient. Also, tracking the design episodes is automatically managed in an independent database and file systems, which can attenuate the difficulties in managing complex design information. As a result, if it is considered based on Goldschmidt's argumentation (2006, p. 106) that design reasoning rests on two types of cognitive strategies, the urban design support prototype can contribute to increasing the rate of design moves. Based on the discussions so far, it is possible to respond to the research questions of Chapter 4.

How can the naturalistic design behavior be supported by the design support prototype? For example, an urban designer can use his or her own experience to solve design problems. Using naturalistic operations such as merging, dividing, and deleting plot(s) in an intervention block area, a user can transform the problematic urban design entities into better ones in consideration of urban form and performance. In this case, the design support prototype responds to the user’s operations to maintain and update topological relations between urban entities. Figure 44 demonstrates a case that the design support prototype updates the topological information of a plot after dividing its incident plot into two. Through these supports that human designers are familiar with, it is possible to develop ideas in a naturalistic manner.

How can the explorative activities in which designers co-evolve the design problem and solution be improved by the design support? The interactive tracking of design episodes is advantageous to the user. The design support methodology allows human designers to navigate multiple design episodes at a different level. For example, if a new idea concerning a particular design problem is introduced at some point, it is required to recall and reinterpret the solutions that were proposed according to the previous idea. After that, the reinterpreted solutions may become a reliable source for new inspiration, which can allow for exploring unknown design spaces. Such an approach is one that human designers can prevent the number of design solutions from continuing to grow. Through this approach, human designers can work on multiple design ideas in different design episodes in parallel, which can enhance adaptability and circularity when compared to the design approaches that are weak at supporting such a navigation capability.

Figure 44 A demonstration of the transformation of plots in an intervention block

How can the generative design support methodology increase explorative opportunities to the design generation path? Human designers have assisted in navigating different design episodes, but they can also be assisted in exploring design solutions. For example, human designers can use design alternatives that are generated with parametric rules of the design support prototype. The parametric approach can offer a wide range of alternative urban layouts for explorations, but it is necessary to keep the number of design alternatives from being not too many to explore them in a meaningful manner manually. So, the design support prototype can present multiple design alternatives to a specific design concept all at once to human designers. Moreover, divergent thinking may be stimulated by the overlapping of states or densely ordered states (Goel, 1995) that are induced by design solution alternatives to a particular design problem. Using the design support prototype, therefore, human designers can be assisted in exploring the design generation path and making more optimal decisions by increasing the opportunities for generating diverse design solutions.

5 Case Study

The design support prototype for interactive exploration of urban design, which has been prescribed in Chapters 3 and 4, is tested through three case studies. A preliminary evaluation describes how the urban design support prototype dealt with the research goals. Upon running the design support prototype, the design process is started by loading the necessary prepared information. The aerial image showing areas nearby is underlaid for a human user to be able to sense the scale of the site by measuring nearby urban entities. In the case of developing ideas for block configurations, a particular algorithm may not be appliable for some of the blocks. In particular, the ratio and size of a block are essential to consider when generating block variants.

For example, when a block is too narrow or small, the generation of a kind of perimeter block typology may not be successful. Instead, a block of tower block typology is expected to be generated. It is supposed to be convenient if the minimal sizes of each urban entity are predefined, or a user can specify the minimum sizes of them. In this way, it helps users avoid mistakes in manual design operations. In addition, in dividing a block into two or smaller blocks, too small entities and even invisible entities can be generated. In the case of using dividing functions among blocks, any resulting blocks that are smaller than the allowed minimum size of blocks are merged into their neighboring ones. The same approach is applied to the plot division operation, which can minimize designers' manual operations to fix undesirable geometric properties.

As the plot generation algorithms are designed to adapt to different boundary conditions, users can apply different plot generation algorithms in order to obtain desirable geometric configurations without considering the properties of the intervention area. The urban fabric can be made by alternating parameter values of urban entities. Alternatively, the generated urban fabric can be transformed globally or locally by controlling the urban entities' relevant parameters. Moreover, human designers can control the urban fabric more directly and more interactively by two principal operations: dividing and merging in the block level and the plot level. The main advantage of using the proposed urban design support prototype is that it is possible to directly transform the geometry, whatever is generated by applying algorithms or manually inserted, which is the interaction that other automated approaches do not support. After transforming urban entities, the design support prototype can recompute connectivity and visibility analyses, which are critical aspects to consider for decision-making. Such an interactive transformation loop can be practiced in a real-time manner.

The proposed methods have been applied and tested in three case study sites (i.e., Lerchenauerstrasse, Eggarten-Siedlung, and Raheinstrasse in Munich, Germany).[13] In particular, the area of Lerchenauerstrasse is an attractive site as it is used frequently for the urban design contest that the City of Munich has hosted. Also, Eggarten-Siedlung is used for urban design contests as well. Eggarten-Siedlung is the smallest area compared to Lerchenauerstrasse and Raheinstrasse but the densest one. Lerchenauerstrasse is used for the design experiment, which will be discussed in the next chapter. The overall building coverage ratio and floor area ratio of the three case studies are represented in Table 15.

Table 15 Building coverage ratio and floor area ratio of the three case studies

	Lerchenauerstrasse	Eggarten-Siedlung	Raheinstrasse
Total area (m^2)	247,590	166,347	441,871
Building Coverage Ratio (%)	29.44	42.59	20.42
Floor Area Ratio (%)	117.35	333.36	108.88

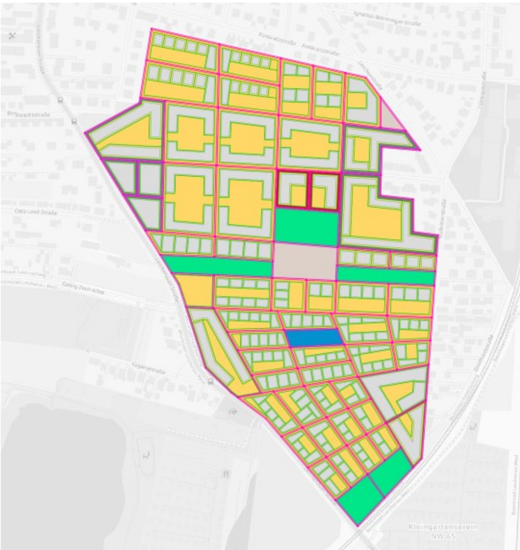
5.1 Case Study A: Lerchenauerstrasse

Figure 45 A screenshot of the prototype with a final design proposal for Lerchenauer Strasse in Munich

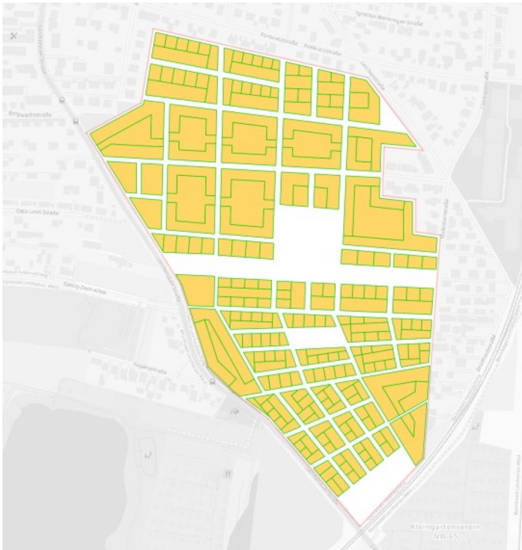
As shown in Figure 45 and Figure 46, the urban design concept has characteristics of horizontal and vertical axes that subdivide the intervention site (Google Maps: http://www.bit.ly/3ja1zsN).

[13] Three case studies' design processes using the implemented design support prototype were recorded directly via a screencast software for the posterior evaluation. Images, urban design data, and process-related data collected, and the recorded screencasts concerning each design process are evaluated by six external raters, which hopefully combine to increase and maintain the evaluation's reliability. For such an evaluation, it is widely accepted that five evaluators suffice and the more tend to increase the reliability, according to Faulkner (2003).

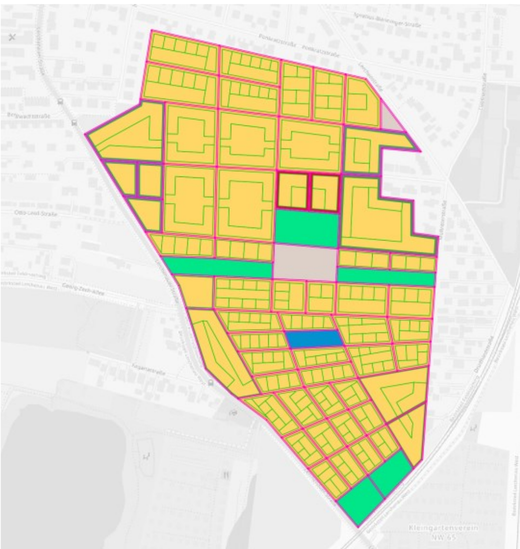
Figure 47 shows each moment's exemplary snapshots during design progress until the final design outcome is reached. This initial concept was decided by considering the nearby areas, i.e., connecting existing road networks and the lake in the southwest. Also, there is a subway station in the northeast. After identifying the site context, multiple axes are drawn from north to south to connect the intervention site to the lake and multiple horizontal lines to connect to the existing road network. After that, larger blocks are gradually divided into smaller ones by considering nearby urban fabric. In the case of defining the green zones, smaller blocks are merged into larger ones. This kind of merging and dividing operations are applied repetitively to distribute the different-sized blocks relatively evenly. It is proposed to allocate several roads and green spaces, which cross from east to west, by considering the existing district-scale nearby.



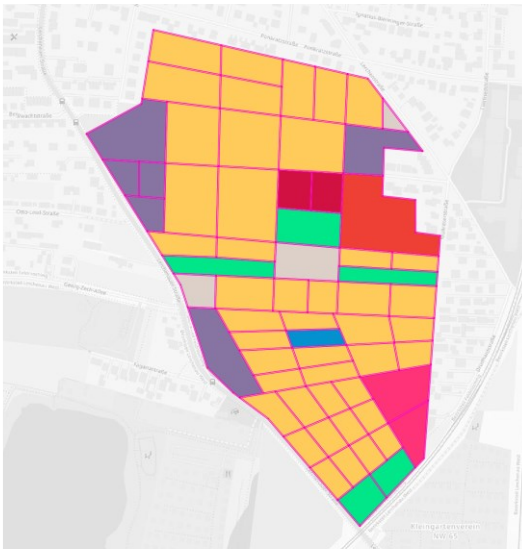
(a) A final urban design outcome



(b) Building layout



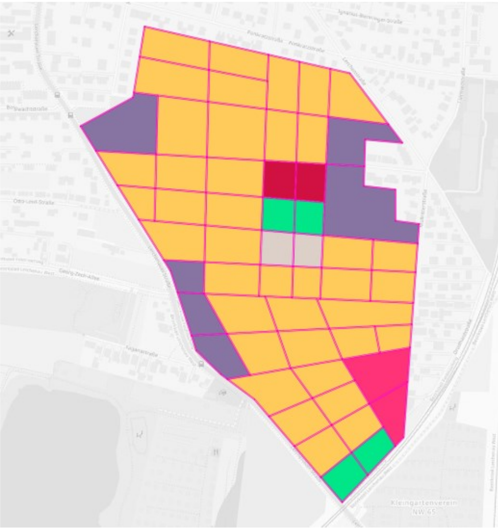
(c) Plot allocation based on the zoning



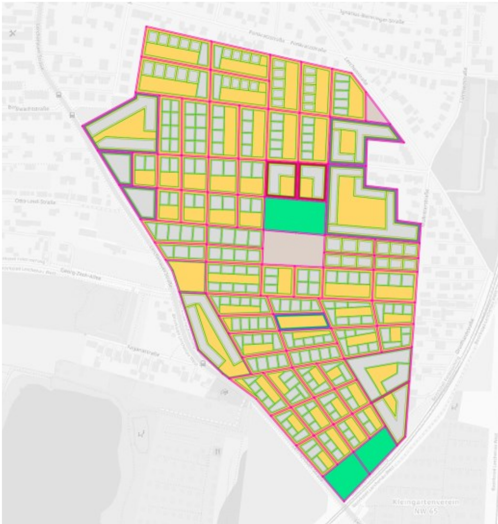
(d) Zoning

Figure 46 Final urban design outcome after ca. 1h 30 minutes design experiment of concept A

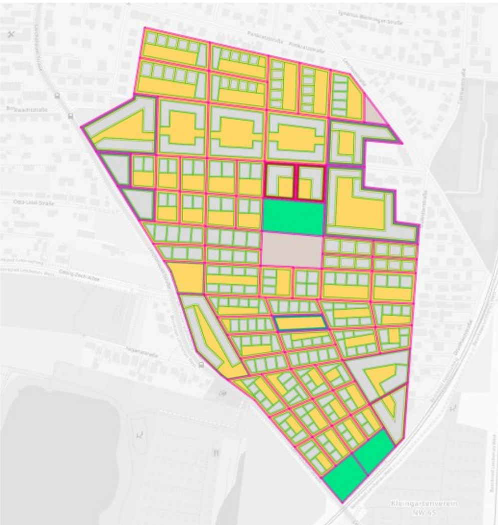
Overall, it tried to allocate water area and open space in consideration of the district area's openness and used divide-and-merge operations effectively. The use of design history navigation is limited because the central concept is decided early and is not changed except for minor modifications in the block level. However, it is used effectively to test different layout configurations when it is tried to avoid the monotonous building type. For the plot allocation, the function of the alternative generation is used when the bounding geometry of blocks is irregular. The function of alternative generation was used four times, for about 1 hour 3 minutes in total, and spent relatively much time to consider a scheme of the block when the blocks have irregular shapes.



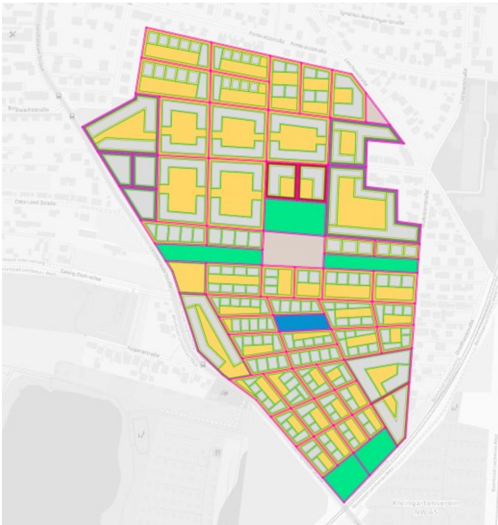
(a) Design session 1: Initial road network and block division based on a zoning plan



(b) Design session 2: Additional block division and initial building generation



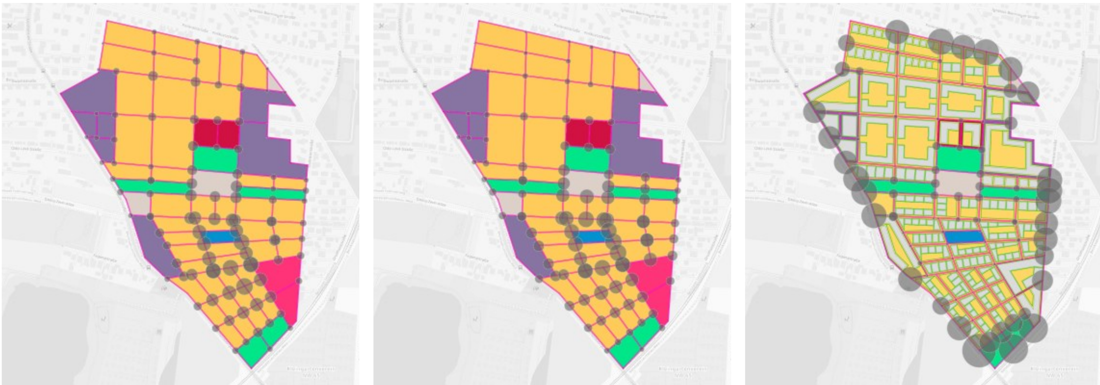
(c) Design session 3: Minor block modification and building volume alternation



(d) Design session 4: The generation of different buildings with various layout typology are practiced.

Figure 47 Snapshots of design progress until reaching the final design outcome in Figure 46

In order to increase the area of the open space, which is accessible from other plots of the intervention site, it is decided to allocate open spaces in the center. The commercial areas are placed in the northwest area, along the Lerchenauerstrasse and another one near the train/subway station by considering a pedestrian network. The education facility is put on near a more dense area surrounded by open space and commercial areas. The low-density housing area is allocated in the south and north areas by considering old town and the access to the green area. After defining the main functions of blocks, the overall design strategy is decided to subdivide larger blocks or extended areas into smaller ones and then change some of the blocks' functions to open space and water park. Figure 48 shows several visualizations of the urban fabric's analytic information in Lerchenauerstrasse, and Figure 49 shows the perspective images of the final design proposal from different viewpoints.



(a) Connectivity analysis by Metric Reach

(b) Connectivity analysis by Intersection Density

(c) Visibility analysis

Figure 48 Visualizations of analytic information of the urban fabric in Lerchenauerstrasse

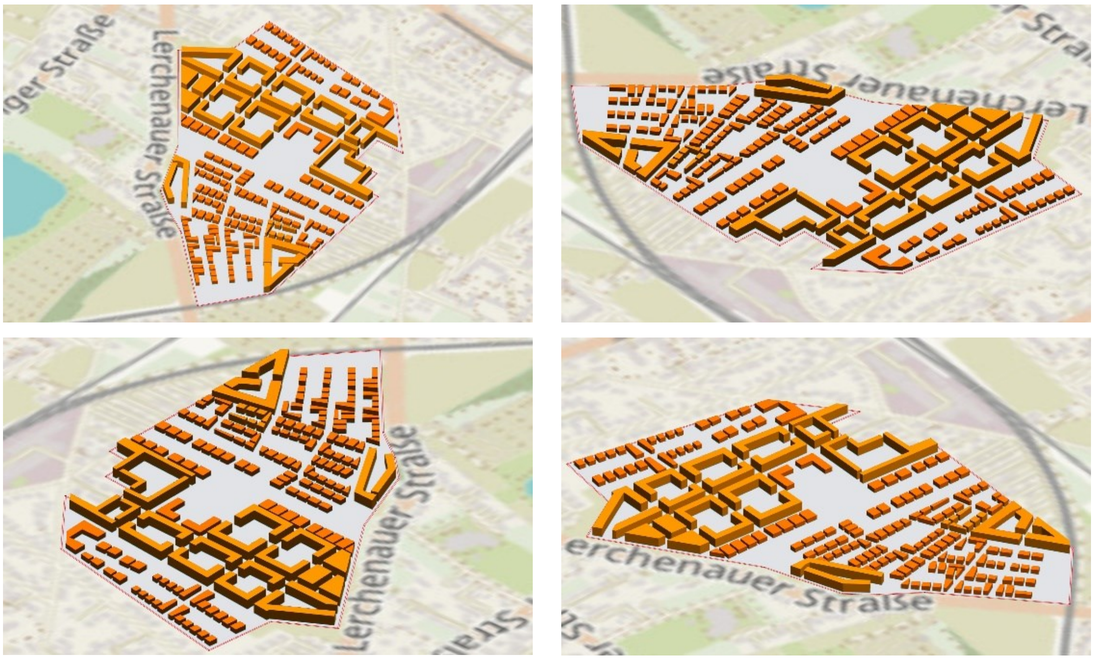
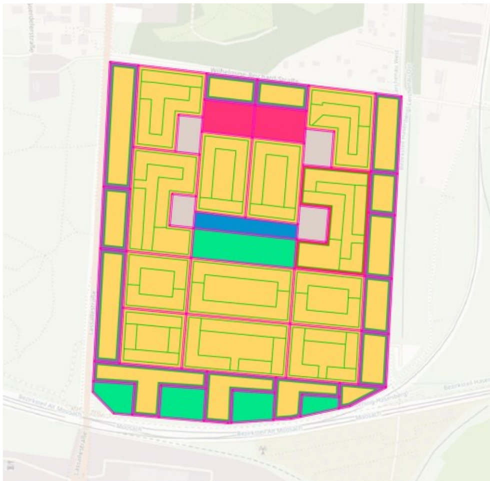


Figure 49 3D Visualization of final design proposal in Lerchenauer-Strasse

5.2 Case Study B: Eggarten-Siedlung

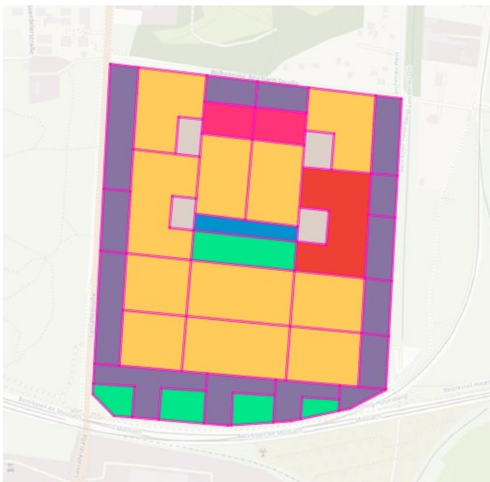
Figure 50 A screenshot of the prototype with a final urban design for Eggarten-Siedlung in Munich

(a) A final urban design outcome



(b) Plot distribution

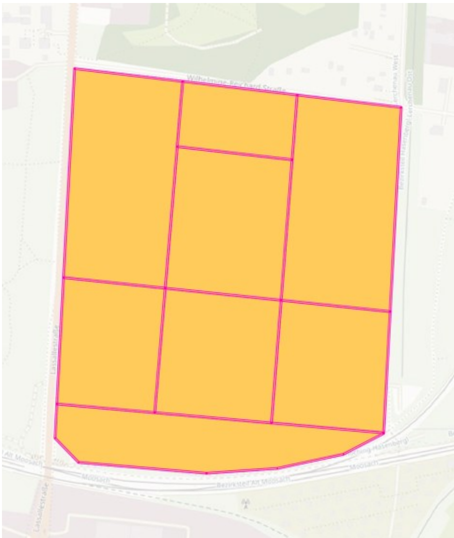
(c) Building allocation based on the zoning



(d) Zoning

Figure 51 Final urban design outcome after ca. 40 minutes case study for Eggarten-Siedlung

Figure 50 shows the screenshot of a final urban design of Eggarten-Siedlung that was developed using the prototype. The second case study's goal is the redevelopment of the Eggarten area (Google Maps: http://www.bit.ly/3kyl0LW) in Munich. The intervention site has a large green area on the left side and faces railways on the south. The urban area features a high-density, mixed-use development near railways and an enclosing road network. The overall idea for this intervention area is to allocate perimeter housings surrounded by commercial buildings. Particularly, high-rise offices near the railroads and along the nearby roads encircle the inner urban fabric. In the central area, open spaces are placed, and each cluster has its own small open area. Figure 51 shows the final urban fabric of Eggarten-Siedlung.



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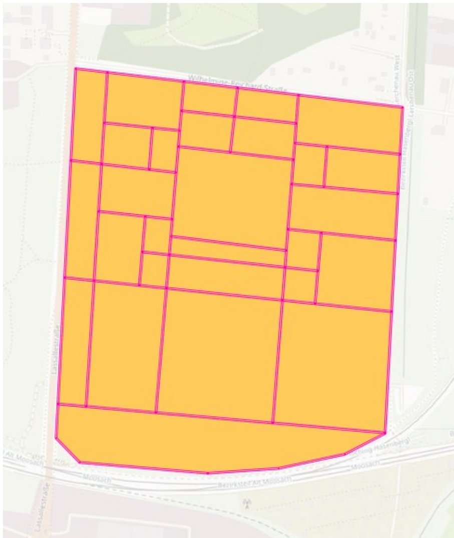
(a) Design session 1: Initial road network and block division are inherited from the existing street network



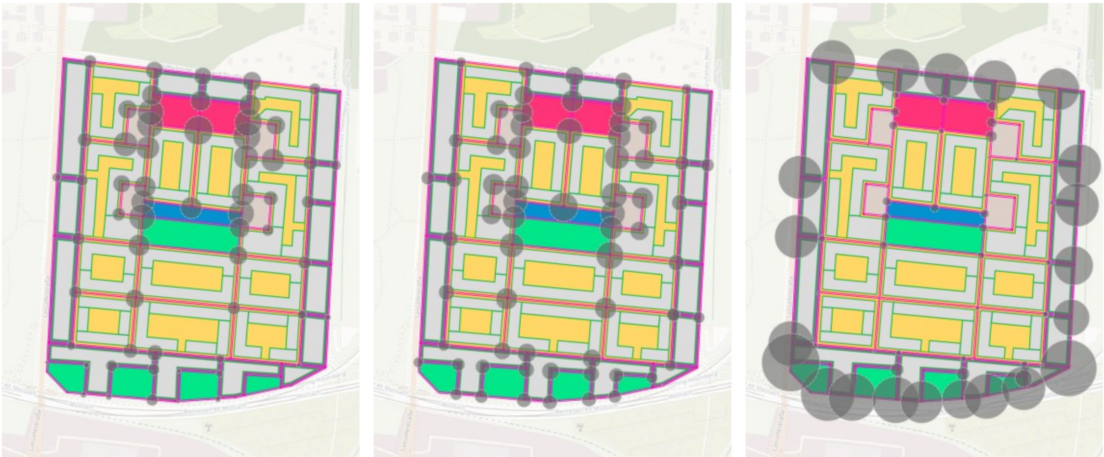
(b) Design session 2: Additional block division considering the neighboring context

(c) Design session 3: Zoning and initial building are defined

(d) Design session 4: Minor modification on the building level, such as building layout and density

Figure 52 Snapshots of design progress until reaching the final urban fabric of Eggarten-Siedlung

Figure 52 shows the snapshots of each moment of design development until reaching the final design of Eggarten-Siedlung. The intervention site of Eggarten-Siedlung has the existing street network, which is decided to be kept for the initial design idea, as shown in Figure 52 (a). About 15 percent of the area among building coverage is allocated for commercials. Additional road segments that divide block areas are inserted by considering zoning (b). Zoning and initial building allocation are proposed (c), followed by a minor alternation of building volumes (d). Overall, designing took ca. 40 minutes. Figure 53 shows the visual representation of the analytic data of the final design proposal. Figure 54 shows the 3D perspective image of the final urban design outcome of Eggarten-Siedlung.



(a) Connectivity analysis using Metric Distance

(b) Connectivity analysis using Intersection Density

(c) Visibility analysis (Radius: 200 meters)

Figure 53 Visual representation of analytic data of Eggarten-Siedlung

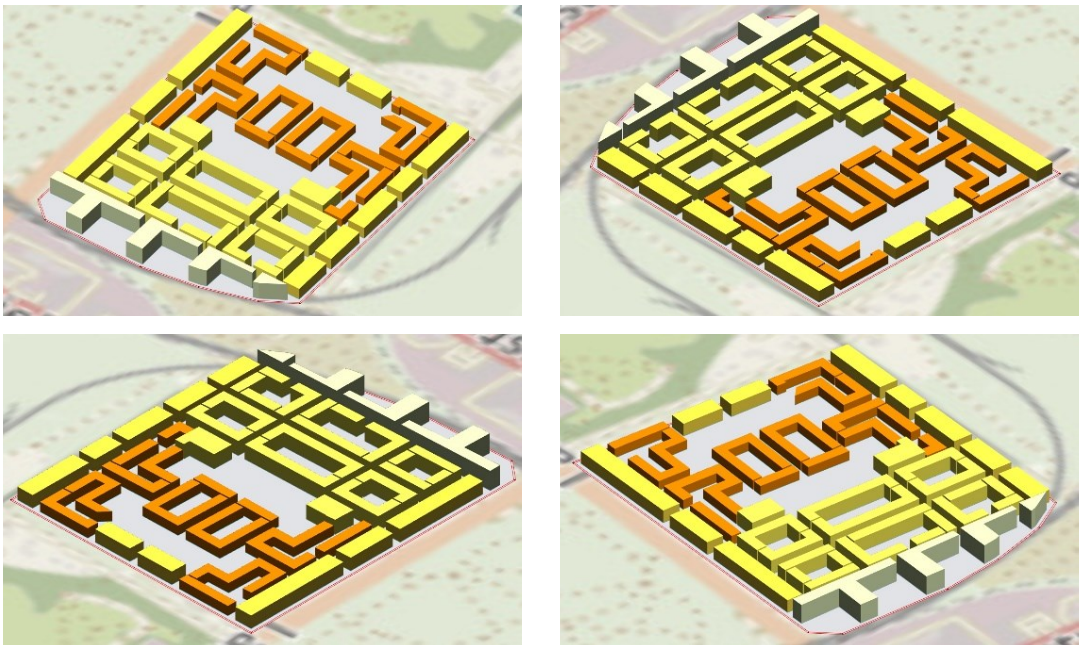


Figure 54 3D Visualization of building configuration of Eggarten-Siedlung

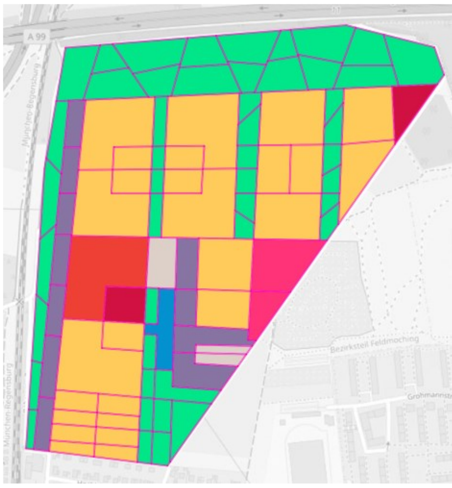
5.3 Case Study C: Raheinstrasse

Figure 55 A screenshot of the prototype with a final urban design for Raheinstrasse in Munich

(a) A final urban design outcome

(b) Plot distribution

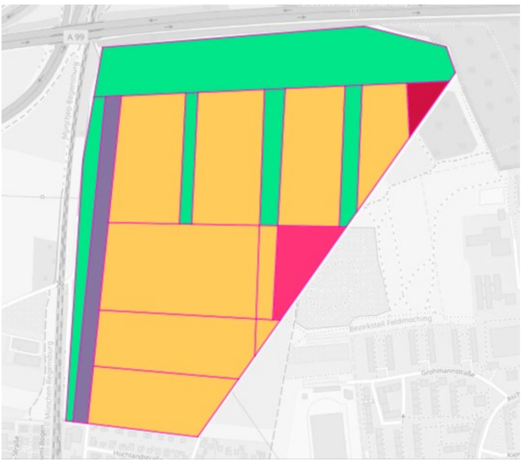
(c) Building allocation based on the zoning



(d) Zoning

Figure 56 Final urban design outcome after ca. 70 minutes design experiment for Raheinstrasse

Final urban design outcome after ca. 70 minutes in the intervention site (Google Maps: http://www.bit.ly/2FNfy9k) in Feldmoching-Hassenbergl, a borough in the northern part of Munich in Bayern, was obtained. Access to this site is restricted when compared to other case study sites. The railway on the west and the highway on the north may reduce accessibility to this intervention site. Therefore, accessibility and noise issues should be considered, and access to the greenery should be utilized. So, a road network that is accessed from the south and east is considered to connect itself to the existing urban fabric. Moreover, the green field on the north and northeast of this intervention site should be considered to be used as an essential natural resource for leisure activity. Figure 55 and Figure 56 show a final urban design for Raheinstrasse in Munich.



(a) Design session 1: Initial road network and block division

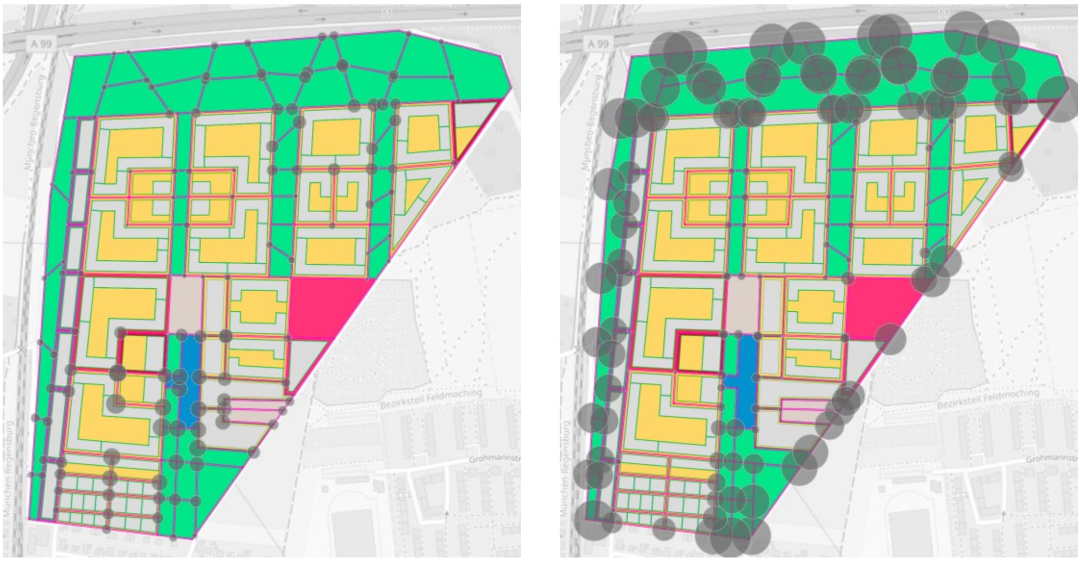
(b) Design session 2: Additional block division and initial building layout generation

(c) Design session 3: Minor block modification and initial plot division are practiced

(d) Design session 4: The generation of a different building with various layout typology are practiced.

Figure 57 Snapshots of design progress until reaching the final urban fabric of Raheinstrasse

Figure 57 shows the snapshots of the design progress until the final urban fabric was reached. The site was divided by initial sketch considering transportation network and overall concept to maximize the access to the green network (a). Based on the initial sketch, blocks are divided further to the manageable level, and initial building layouts are generated by considering zoning (b). Building volumes are generated considering overall density and building height (c). Lastly, missing road network and buildings are added, and minor modification is practiced on the green and open area to enhance the accessibility to this intervention site. Figure 58 shows the visual representation of the analytic data of Raheinstrasse. In particular, the visualized connectivity analysis is used to identify if the open area can be accessed easily, which can help make a decision. Figure 59 shows the 3D perspective image of the final urban design outcome.



(a) Connectivity Analysis using Metric Reach (b) Visibility analysis

Figure 58 Visual representation of analytic data of Raheinstrasse

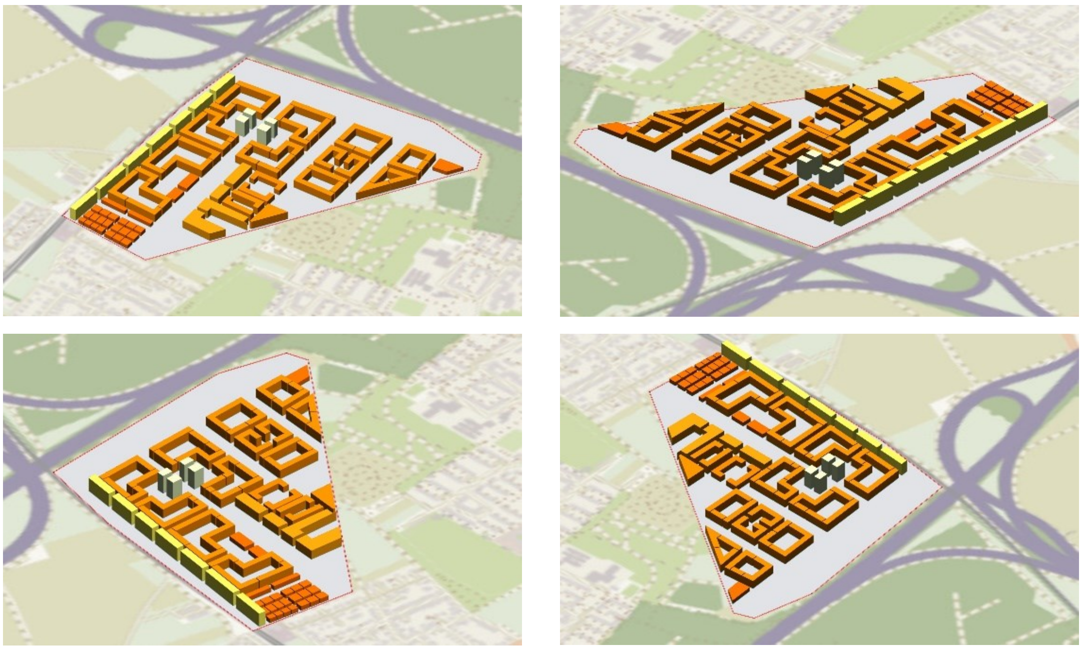


Figure 59 3D Visualization of building configuration of Raheinstrasse

5.4 Summary of Case Study

In this Chapter's scope, three case studies are presented to demonstrate the application of the interactive explorative methodology for urban design. The prototype's computational support includes divide-and-merge operations, the automated generation of block alternatives, tracking of design history, and the use of connectivity and visibility analysis. Based on three exemplary case studies, it has been shown that this interactive explorative method can be appliable to produce feasible urban design concepts in the early stage. Substantial urban ideas can be explored and tested by using the interactive prototype.

A further effort should be required to enhance design activity; however, it can be concluded that the implemented divide-and-merge operation in the block level and the plot level provides a sound basis for flexible urban entity synthesis. Through the automated generation of urban alternatives, the individual can be supported to widen or deepen ideas, i.e., divergent thinking and convergent thinking at the block level and plot level. Moreover, ideas that are produced through the design process can be managed systematically, which allows for the development of feasible ideas flexibly.

Securing a certain level of reliability of the implemented urban design support prototype is indispensable for conducting a design experiment that will be further discussed in Chapter 6. In order to evaluate the aspects of the urban design support prototype and three case studies, a posterior survey was conducted voluntarily by six external evaluators, who are independent of this research. The survey that were requested to the six evaluators[14] includes seven questions concerning: 1) The level of their familiarity with the use of digital design and analysis tools, 2) The level of simpleness and easiness of the prototype of the urban design support (i.e., easy handling of geometric and topological information of urban entities by dividing and merging operations) that may be enough to use for developing urban design concepts, 3) The level of efficiency of the prototype of the urban design support (i.e., a human designer can develop ideas

[14] Considering each evaluator's expertise and experience, I am assured that they are qualified enough to evaluate diverse aspects of the urban design support and design outcomes using the design support. Two evaluators (Evaluators Y and N), who participated in the design experiment, are active architects whose tasks include BIM-based architecture design. Evaluator T, who previously worked at design/construction firms, is an experienced designer and engineer currently providing CAD/BIM solutions for building construction and MEP. Evaluator I is an experienced architect who provides various cloud-based BIM design services. Evaluator J's main task is establishing UX design guidelines and evaluating the UX design of consumer electronics and home appliances. Evaluator E is an expert in the field of building energy simulation, in particular, knowledgeable about the author's implementation of the proposed design support prototype and the design experiment before conducting the design experiment.

by interactively manipulating urban entities' geometry and parameter values) for developing urban design concepts, 4) The level of workability of the provision of the generated design alternatives, 5) The level of workability of the design history navigation to record design ideas and to reuse them, 6) The level of the design support prototype for idea generation during the early design stage, and 7) The level of workability of the design analysis modules for making more informed decisions.

A 6-point Likert scale is used to get responses from each evaluator, who concluded that all aspects work well as intended, therefore evaluating the urban design support favorably. Furthermore, it is assumed that evaluating the prototype's functional aspects and three case studies objectively can be achieved. Therefore, the urban design support prototype runs well enough to explore various ideas interactively, which is also supported by the participants' responses that are discussed in Section 7.1. Key aspects after the application of the prototype in the three case studies can be summed up as follows:

1. Geometric and topological information of urban entities is preserved throughout the design process, which can eventually alleviate human designers' cognitive workload.
2. Even though the design alternatives of a block are generated in part using random values, it does not affect the whole design idea of intervention sites as only the area of interest is to be transformed selectively. The prototype allows a human designer to develop ideas by interactively manipulating urban entities' geometry and parameter values.
3. A few advanced urban analyses are integrated into the prototype's design workflow, as can be implied by the case study of connectivity and visibility analyses. They can provide prompt feedback on the performance of an urban design idea. Human designers can use those analytic methods for more informed decision-making because a minimum level of data required to run the analysis is prepared.

Concerning the issues in design creativity, the proposed approach helps overcome a few limitations that are identified in the automated generation of urban form. In many cases of using automated algorithms for form generation, as discussed in Chapter 2, human designers have restricted control over the generation and distribution of urban entities (e.g., plots). Human designers have little capacity to get involved in idea development, as preset parameters and data lead the generation and allocation of urban entities. For example, human designers can interactively lead the design process to decide the desirable allocation of the blocks, plots, and buildings, independent of being restrained by the defined control parameters.

6 Experiment

This chapter presents a design experiment that aims at investigating how the design approach using the implemented urban design support prototype would benefit designers during the concept generation of urban design. In particular, it is focused on how the difference in the modalities of user interaction (i.e., the design approach using the proposed urban design support prototype) influences the development of unique design ideas, design feasibility, and design quality. This is because the user interaction with the prototype can be influenced by the diverse cognitive patterns of human designers, affecting their design outcomes. The experiment examines the influence of the implemented design support prototype on how designers generate design outcomes, which depends on the type of supports and interaction practiced by the designer. The hypothesis that is introduced in Section 1.2 is:

"The proposed interactive design approach can encourage a human designer to find urban design ideas effectively."

This hypothesis will be tested, focusing on the two aspects that are implemented in the interactive urban design support prototype, which are: the generation of multiple block alternatives, and the management of the design history, which enables backward-tracking and side-tracking of design states. So, the two sub-hypotheses that are used to address the main hypothesis are:

Sub-hypothesis 1: The design with the support of design history navigation will help find unique design ideas, which enhance design creativity. It is because flexible tracking and reuse of design sessions can enhance the possibility to examine more authentic ideas. This is measured with an originality metric, as explained in Session 6.3.

Sub-hypothesis 2: The design with the support of the design variant generation will produce a higher quality design. It is because the provision of design alternatives from the proposed design support prototype can stimulate the human designer for divergent thinking and convergent thinking. This will be measured with an appropriateness metric, as explained in Session 6.3.

Accordingly, the effects of using the proposed urban design support prototype as an aid for concept generation were tested in a design experiment based on realistic design scenarios, as explained in Sections 6.1 and 6.2. Four metrics (i.e., novelty, variety, quality of concepts, and the number of non-redundant ideas) are considered to evaluate the urban design ideas that design task participants suggested. The feedback of design task participants will also be analyzed to identify aspects concerning urban design idea development using the proposed design support prototype. It is to determine how useful the proposed computational design support is in improving conceptual design generation.

6.1 Urban Design Task

The purpose of the urban design task is to test the validity of the urban design support's research concept. In order to examine the effects of the design support methodology on urban design, an open-ended design problem should be tested with longer session times but may allow the participant to complete the experiment within a single sitting. So, the urban design task should be appropriate, challenging, and realistic for the task participants, not too large, not too small, in order to be more representative of an urban design problem in an early design process. The assignment needs to be typical for urban design, as it requires the integration of a number of aspects, such as economic, socio-cultural, environmental, form-giving, and aesthetic. Design task participants were asked to generate ideas for the given urban design assignment, given time to identify design problems and generate urban design solutions. Table 16 shows the problem description, design aspects to consider provided to the task participants. Among the sites that are used for case studies in the previous chapter, the area of Lerchenauerstrasse is used for the design experiment. Except for the streamlined design brief, accompanied by several critical pieces of information, I limited the amount of background information available to each participant. The design assignment's problem statement is, "***try to propose a new living area, suitable for this urban context***." At the beginning of each design task, the assignment was introduced and briefly discussed. The urban design task given to the participants asks them to design an urban masterplan, which will be conducted within 2 hours, if possible. Besides gathering sketches and digital designs, verbal data will also be recorded to identify what the participants think as much as possible. In order to address how the use of urban design support affects design development, quality, and creativity in the urban design idea generation process, the relevant information is collected and analyzed. The experiment will occur in a controlled design studio setting. The design task participants will be asked to propose a single creative design concept that may achieve high quality.

Table 16 A description of the urban design problem and aspects to consider, provided to participants

Design problem	Designing of a modern town in the suburban area (Lerchenauerstrasse) of Munich, Germany
Problem description	In a city like Munich, the shortage of housings has become a growing problem. This urban design assignment aims to plan a low/middle rise new town in the eastern part of Munich. The target density of the new town is between 4,500~4,700/km2.
Aspects to consider	Maximize green area Mixed functions Increase social cohesion Increase the quality of open spaces Protect privacy Access to the open space

6.2 Participants and Experimental Procedure

A design experiment is designed to test the hypothesis that the proposed interactive design approach can encourage a human designer to find urban design ideas effectively. First, the subjects proposed an urban design to an urban design test set. The urban design support prototype can record generated data such as the screen images, urban design alternatives based on the subject's activities while operating the design support prototype. Also, as to the in-depth evaluation of the design process that cannot be captured in the urban design support prototype, the subject's activities were video-recorded and verbal think-aloud were voice-recorded. Rather than analyzing the processes to identify the degree of creativity by analyzing the protocols using a particular protocol analysis model, it is used to more clearly understand the outcomes produced as it is hard to grasp the design intention. Both quantitative and qualitative data, including think-aloud protocols (Ericsson and Simon, 1984), were collected. All participants and their outcomes are anonymously identified by codes so that their personal identities should not be disclosed. For each participant, I obtained an informed consensus. In total, eighteen individuals participated in the design experiment, but 14 out of 18 individuals could complete their design tasks for various reasons.[15] As shown in Figure 60, the task participants consisted of fourteen architects ($N = 14$) with a mean age of 35.3 years ($SD = 6.4$ years) and a mean of 4.2 years ($SD = 3.7$ years) of relevant design experience. Four task participants (33.3%) were female, and the rest ten task participants (66.7%) were male. Concerning the design experiment procedure, a short introductory tutorial of the prototype to each participant was given separately for about half-hour. Right after the tutorial, each participant had an opportunity to get accustomed to the prototype for approximately an hour. During the design experiment, they could ask how to use the functions of the design support prototype. After that, each participant is given about two hours for the development of urban design ideas, but there was no regulation on the duration of the design development. Most participants spent about two hours, but there were one case that a participant

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[15] As far as is known, there is no clear-cut answer for the correct sample size required for such a design experiment. For usability tests, it is widely accepted that 5 participants suffice and the more tend to increase the reliability, according to Faulkner (2003). For example, in Akin and Akin (1998)'s study on the sketch-based design experiment, design results from a total of eight designers were analyzed to test their hypothesis. Ball, Ormerod, and Morley (2004) recruited eight expert designers and eight novice designers in their study to explore the nature and prevalence of spontaneous analogizing in design contexts. As a rule of thumb, it is assumed that the sample size in this design experiment is sufficient to identify how the proposed design support influences the participants' outcome. Furthermore, recruiting more experienced volunteers was unfortunately limited, attributed to the COVID-19 pandemic when the design experiment was conducted. I want to express my deepest gratitude to all architects who voluntarily decided to participate in the design experiment during this challenging time.

spent a little over an hour, and the other case that a participant spent two and a half-hour in completing the urban design test. Even though there is no consensus on the right scale of the design experiment, I think the number of fourteen architects is suitable for such a kind of study in that the expected outcomes can be varied enough to verify the research hypotheses. As all task participants are active in design projects, I expected each architect to have a certain level of knowledge in urban design and to be very fluent in idea generation. Also, it is identified that they mostly have fluent skills in designing and handling CAD tools.

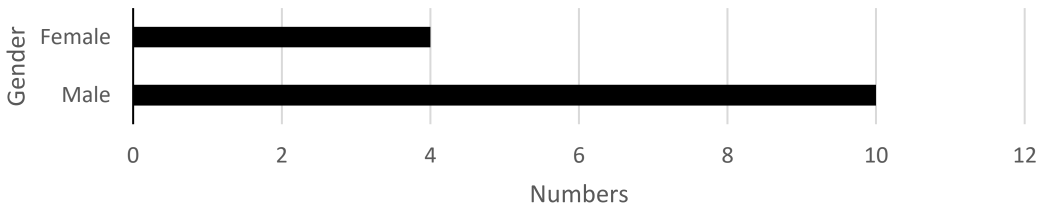


Figure 60 Participants of design experiment using the prototype

In order to make this design assignment suitable for application in creative urban problem solving, only a brief problem statement, “Try to propose a new design of settlement in this area,” which was accompanied by some of the critical information, is given to each task participant. Also, the amount of background information available to each participant is limited, as suggested by creative problem-solving methodology (Isaksen, Stead-Dorval, and Treffinger, 2011). All participants voluntarily attended the urban design experiment. In summary, the design experiment consists of three phases:

- ***Phase 1***: Before the beginning of each test, the design assignment was introduced, along with the critical pieces of information concerning the intervention site. Furthermore, to help each participant familiar with the design support prototype, a short tutorial is given to each task participant. While they practice the design support prototype, they were encouraged to ask questions concerning the experiment and design task.
- ***Phase 2***: After the introduction in Phase 1, participants engaged in about 120-minute urban design tasks using the think-aloud method. During this time, I requested them to propose an innovative urban design proposal, which is feasible and unique. Images and CAD data that each participant produced in the design support prototype are saved, and the participants’ activities were recorded for the later analysis of the design activity.
- ***Phase 3***: After the end of designing, they are asked to explain the proposed urban design concept. Also, additional information that each participant could not specify in the final design concept is identified. In order to identify each participant’s opinion about the use of the design support prototype, a questionnaire survey is asked to fill in, which is discussed in Sections 7.1 and 7.2.

6.3 Creativity Assessment

Figure 61 Examples of urban designs from test participants

In order to evaluate the effectiveness of the proposed urban design support methodology, an evaluation method needs to be developed for analyzing how the design support prototype affects the outcomes out of conducting creative urban design assignment tasks. It is identified that there are two approaches concerning what should be measured and how it should be measured: a process-based approach or an outcome-based approach (Shah, Smith, and Vargas-Hernandez, 2003, p. 115). Whereas the process-based approach analyzes the aspects of the process during the given tasks are being solved, the outcome-based approach focuses on evaluating the results of tasks given. Considering the complication of the urban design task, analyzing the outcomes is relatively simple to accomplish, and the metrics used for measuring the level of creativeness of the design outcomes are well-known in the field of design studies. Therefore, the outcome-based approach, which simply evaluates the outcome, is used in this study. However, if it is judged difficult to identify design intent or meanings solely based on the final design, the captured data during the process is examined retrospectively for more accurate evaluation. Figure 61 shows the urban design outcomes of the test participants.

I will illustrate the evaluation of this group of urban design ideas only at the conceptual stage. First, one must choose the attributes on which creativity assessment is to be based; In order to measure creativity and the overall effectiveness of the design solutions that each designer generated, four metrics are identified, which were initially developed by Shah, Smith, and Vargas-Hernandez (2003): novelty, variety, quality of concepts and quantity of non-redundant ideas. However, two metrics for measuring the number of non-redundant ideas generated and for measuring the variety used to determine the solution space explored by each participant are not adapted for creativity measurement by the raters. The rationale that these two metrics are excluded is that each participant was asked to generate a single solution at the end; therefore, it is difficult to measure the variety among design solutions. Furthermore, no method for measuring an urban design's creativeness has been suggested as far as known. Therefore, based on several existing methods for assessing artifacts' creativeness, two metrics, 'originality' and 'appropriateness,' are used to assess an urban design's creativeness.

Originality measures how unusual or unexpected a particular idea is compared to those produced by other participants (Shah, Smith, and Vargas-Hernandez, 2003), including their own ideas. One way of assessing the degree of an urban design's originality is to compare the characteristics or features of the urban design with other urban designs, which are meant to fulfill the same requirements. For example, if an urban design with high aesthetics, unique and not resembling other urban designs, it is possible to evaluate that the urban design's originality is high. The following steps are carried out for assessing the relative degree of originality of design outcomes.

- Step 1: The raters assess the originality of each urban design on a six-qualitative scale: 'Extremely high originality,' 'Very high originality,' 'A slightly high originality,' 'A slightly low originality,' 'Very low originality,' and 'Extremely low originality.'
- Step 2: The qualitative originality value of each urban design in Step 1 is converted into a quantitative one, as follows: Extremely high originality = 100, Very high originality = 80,

A slightly high originality = 60, A slightly low originality = 40, Very low originality = 20, and Extremely low originality = 0.

- Step 3: If more than one urban design falls in the same degree of originality, intermediate points can be assigned to those considered unique and original.

The appropriateness of ideas measures the feasibility or quality of the design solutions and, in this research context, how well it comes to meet the design aspects to consider (Shah, Smith, and Vargas-Hernandez, 2003, p. 117). In the description of the urban design problem, which is provided to the participants, six aspects should be considered, such as “Maximize green area,” “Mixed functions,” “Increase social cohesion,” “Increase the quality of open spaces,” “Protect privacy,” and “Access to the open space.” These urban design aspects are used to assess an urban design's overall appropriateness and are weighted equally.

The following steps are carried out for assessing the relative degree of appropriateness of design outcomes.

- Step 4: The raters assess the appropriateness of each urban design in consideration of six aspects respectively, on a six-qualitative scale: ‘Extremely high,’ ‘Very high,’ ‘A slightly high,’ ‘A slightly low,’ ‘Very low,’ and ‘Extremely low.’

- Step 5: The qualitative values of six aspects of each urban design in Step 4 are converted into quantitative ones (Extremely high = 100, Very high = 80, A slightly high = 60, A slightly low = 40, Very low = 20, and Extremely low = 0). The sum of these values is divided by 6 to represent the relative degree of appropriateness of an urban design.

As an urban design solely with high appropriateness or solely with high originality cannot be considered creative, as discussed in Subsection 2.1.4, the degree of the creativeness of an urban design can be expressed as a function of these two, ‘originality’ and ‘appropriateness.’ Therefore, the relative degree of the creativeness of an urban design idea is calculated as a product by the multiplication of its degree of originality and appropriateness.

In urban design, the selection of originality and high appropriateness, therefore creative urban designs in a particular site are commonly dependent on the experienced designers' knowledge. Nowadays, experienced designers are frequently invited to judge the urban design proposals in design competitions. Five architects evaluated the urban design results (i.e., from ‘P_A’ to ‘P_N’) that each participant produced. Their work experience at a practicing company exceeds ten years, and they are experts in architecture and urban design. They are given fourteen design outcomes from the design experiment and an evaluation sheet that explains the evaluation process and criteria.

7 Experiment Analysis

In Sections 7.1 – 7.3, I present results that address the analysis of participants' responses to the questionnaire after the design experiment and describes the significance and implications of these results according to each experimental metric. The analysis of the participants' responses to the questionnaire intends to identify their individual opinions about the developed design support prototype and design experiments, which can be used for evaluating the proposed methodology. Also, through the evaluation of the design outcomes, it is possible to know what aspects of the design support can contribute to developing good urban design ideas.

7.1 Analysis of Participants' Response to the Questionnaire

After completing the design experiment, participants were asked to fill in a research questionnaire. The participants' feedback can help evaluate the urban design approach's effectiveness by using the prototype, making improvements, and planning further studies.

A 6-point Likert scale is used for getting responses, and the order of questions in the survey is re-organized in the following text. The main reason to choose the 6-point Likert scale for this survey is that it may force survey takers not to pick the neutral options when they do not want to put thought into the question, compared to most Likert scales with five or seven possible choices. Later, the average of responses to each question is converted to percentile to help to understand the responses intuitively. In total, thirteen questions are asked to fill in as follows, but Question-5 and Question-7 are supplements to Question-4 and Question-7, which requires the participants' empirical opinions which specify a particular property why both the provision of design alternatives and the use of design history navigation are helpful, respectively.

Question-1 is, "*Do you think that you are familiar with the use of digital design tools?*" What may be assumed is that individuals' familiarity with digital tools can influence the output of the design experiment. I assumed that familiarity with the digital tools has no significant influence on the outcome because the prototype's user interface seems simpler than other commercial software. It is implemented for being easy to operate without in-depth knowledge as possible. Moreover, their understanding of the CAD tool can influence the level of learning of the prototype. However, an equal opportunity to practice the prototype is given to the task participants before each test. As shown in Figure 62, except for participant J, who indicated his unfamiliarity with commercial CAD software, thirteen participants indicated that they are very or extremely familiar with commercial CAD software. I guess that participant J indicated that he is slightly unfamiliar with commercial CAD software because he is still studying; therefore, less opportunity to practice CAD tools. However, I assume that participant J could use the design support prototype as effectively as other participants after practicing it.

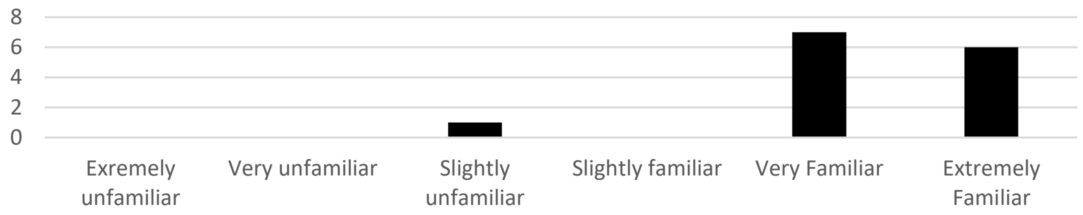


Figure 62 The level of participants' familiarity with CAD tools

Primary operations in the prototype are implemented based on additive, divisional, and superimposing approaches, which are mostly used to relate parts to the whole, as discussed in Subsection 3.2.3. Even though each participant was given an equal opportunity to exercise the prototype for a limited duration, i.e., for about an hour, I want to know if the participants accepted that the prototype is manageable enough to develop their own idea. Question-2 is "*Do you think the prototype of the urban design support system is simple and easy enough to use for developing urban design concepts?*" The average of the responses to this question is 0.8, which indicated that the use of the prototype is convenient for developing urban design concepts. Twelve participants agreed that the prototype is moderately or extremely simple and easy to operate the prototype, as shown in Figure 63.

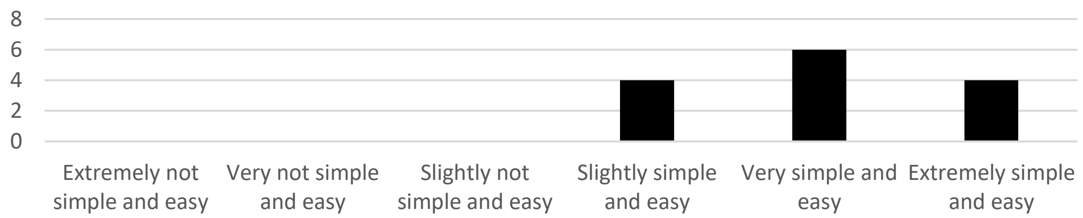


Figure 63 Participants' response to the level of simpleness and easiness of the prototype

In relation to Question-2, Question-3 is, "*Do you think the prototype of the urban design support system is efficient for developing urban design concepts?*"

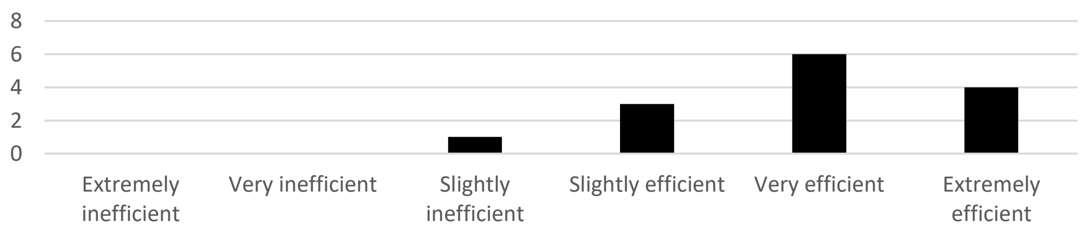


Figure 64 Participants' response to the level of efficiency of the prototype

Most participants replied that they could use the prototype efficiently. The average of the responses to Question-3 is 0.78. Figure 64 shows that three participants indicated that the prototype is slightly efficient, six participants think moderately, and four participants evaluated that the use of the prototype is extremely efficient for developing urban design concepts.

Question-4 is related to the usability of the generation of design alternatives, as shown in Figure 65. The question is, "*Do you think that the provision of design alternatives helps develop your design ideas better?*" The average of the responses to this question is 0.78, which can be interpreted that participants think that the provision of design alternatives helps develop design ideas better. In relation to Question-4, I want to identify which aspects the participants thought helpful while using design alternatives provided by the prototype. Participant J described that he could consider new ideas by reflecting on what is generated. Participant D thinks that the provision of design alternatives sometimes gave an opportunity to consider ideas for more irregular patterns. Participant C pointed out the possibility that the user can see and compare diverse patterns of an urban block, which allows for developing new urban design concepts. Participants H, I, K, and L emphasized that it saves time for developing design concepts. Based on the responses to the fourth and fifth questions, I assume that the provision of design alternatives can increase the chance of developing better design ideas by stimulating human designers and saving time.

Figure 65 Participants' response to the provision of design alternatives in the prototype

Question-6 is related to the use of back-tracking and the side-tracking of design episodes. The question is, "*Do you think that the use of design history navigation helps develop your design ideas better?*"

Figure 66 Participants' response to the use of design history navigation in the prototype

Figure 66 shows that eight participants (56%) find the use of design history navigation is extremely helpful for developing their ideas better; four participants (28%) find it slightly helpful, and two participants (14%) indicated that it is very helpful. The average response to the sixth question is 0.85. Even if there is a case that a participant rarely used the design history navigation to reuse other design ideas, most of the test participants find the use of design history navigation helpful for developing design ideas better.

In relation to Question-6, I want to identify what aspects the participants thought helped develop design ideas better when they used the design history navigation. Participants described various advantages from the use of design history navigation. Participants A, B, and H used the design history navigation to save design ideas separately, which allows for modifying and updating ideas conveniently. Participant C could derive various ideas simultaneously based on a former abstract idea, and Participant I found it convenient to apply various ideas without fixing conditions in the early design stage. Participants D and E could be assisted in memory structuring, which helped look at former ideas and remember design development. Particularly, participant E evaluated it favorably in a way that the design history widget represents ideas as a kind of 'trace-map,' so he could decide which ideas are to be kept or not. Participants G, J, L, and N used it for reviewing the design process, for easy looking-up the history of the design process, which was helpful to figure out how overall ideas had been developed. Participants K, L, and M used it to compare different ideas while keeping previous ideas; otherwise, ideas might be thrown away without much or careful consideration. As time was running out, participant F experienced it is difficult to use the design history navigation. However, he evaluated the use of design history navigation during the design process favorably.

Figure 67 The level of participants' immersiveness during the design experiment

Question-8 is to identify how well each participant could focus on design development using the prototype. As diverse factors can influence participants' degree of being immersed in design activity, I limited the focus on the relation between the use of the design support prototype and the level of being immersed. The question is, "*Do you think the use of the design support system help you being immersed in the design activity?*" The average response to this question is 0.78, which indicates that participants' level of being immersed in their design activity with the design support prototype is high. As shown in Figure 67, five participants (35%) were very immersed, and another five (35%) were extremely immersed. Two participants (14%) were slightly not immersed, and the remaining two (14%) were slightly immersed.

Question-9 is to identify how proactively test participants developed their design ideas using the prototype. The question is, "*Do you think you developed design concepts proactively?*" As shown in Figure 68, four participants (28%) indicated that they tend to develop design ideas slightly inactively or actively. However, ten participants (72%) gave the opinion that they could develop their design concepts very or extremely proactively. When we reflect on the response to Question 4 and Question 6, these opinions may be interpreted that the provision of design alternatives and the use of design history navigation did not interrupt the participants' creative activity.

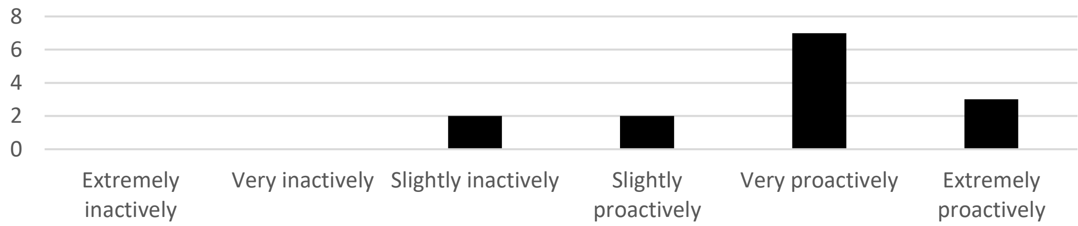


Figure 68 The level of participants' proactiveness during the design experiment

Question-10 is "*Even the duration of the design experiment was not enough, are you satisfied with the final outcome?*" Concerning the participants' satisfaction with the design outcome, only two persons (14%) were very dissatisfied with their outcome. It is identified that their design ideas could not be fully developed design ideas within a given time. Nevertheless, the average of the responses to this question is 0.72, which can be interpreted that the participants are satisfied with their design outcome. Particularly, three persons (21%) are slightly satisfied, five persons (35%) are very satisfied, and four persons (28%) are extremely satisfied with their design outcome, as shown in Figure 69.

Figure 69 The level of participants' contentment of their design outcome

Even if design participants had an opportunity to use the prototype during a limited time in the design experiment, I wanted to know their expectations about the interactive explorative approach to urban design. Question-11 is, "*Do you think the urban design support tool can be used for idea generation during the early design stage?*" The average response to this question is

0.88, which can be interpreted that the participants appreciated the interactive explorative approach, as shown in Figure 70.

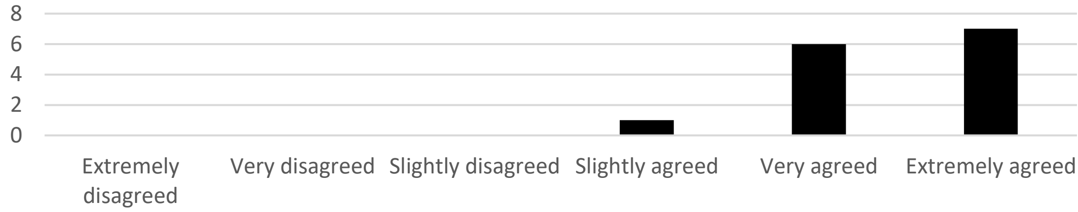


Figure 70 Participants' expectation of the future use of the urban design prototype

Question-12 is to know how helpful the use of the design analysis module is for participants to make more informed decisions while developing ideas. The question is, "*If you used design analysis modules, do you think the use of design analysis modules helps make more informed decisions while developing ideas?*" All participants but one answered this question. The average response to this question is 0.86%, which can be interpreted that the use of the analysis functions is advantageous when participants evaluated their design idea, as shown in Figure 71.

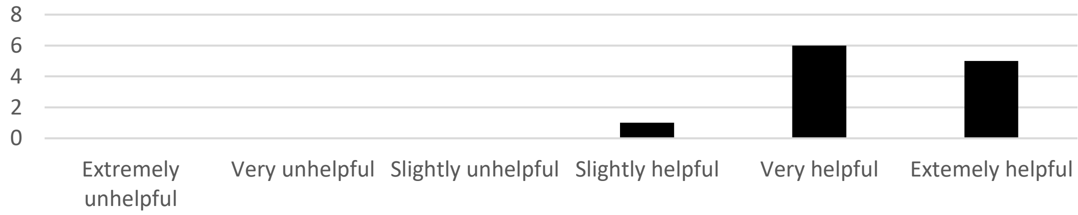


Figure 71 Participants' response to the use of design analysis modules

Question-13 aims to identify each participant's familiarity with urban design. The question is, "*Before the design experiment, do you think you are familiar with urban design?*" The average response to this question is 0.52%. The distribution of participants' responses to this question is, as shown in Figure 72. That is, one participant is extremely knowledgeable about urban design, five participants (42%) acknowledge their high familiarity with the urban design, three are slightly familiar, another three are very unfamiliar, and two are extremely unfamiliar with urban design. However, it is identified that most participants do not have work experience that dealt with such a large scale of the urban design task given.

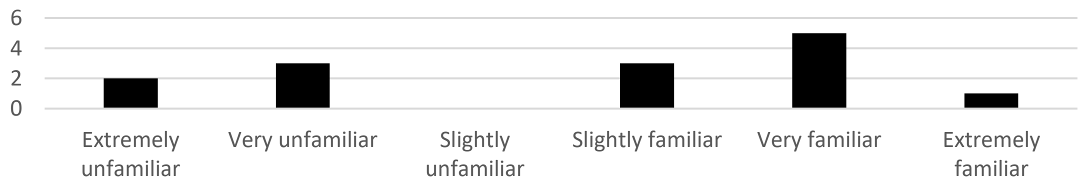


Figure 72 Participants' response to the level of familiarity with urban design

7.2 Correlations of the Responses to Different Aspects of the Prototype

In order to identify the relations among the responses to different aspects of the prototype used in this design experiment, a correlation analysis was conducted over the responses to the entire 11 questions. Compared to A2 and A3, which are related to the participants' overall opinions about the prototype, A4, A6, and A12 are related to their opinions about particular functions, such as the provision of design alternatives, design history navigation, and design analysis, respectively. In addition, A8, A9, and A10 are related to their experience during design development using the prototype. To carry out the test, I first assigned values to the Likert responses. For example, in the case of the responses to Question-13, I could assign a value of "0" for "extremely unfamiliar," "1" for "very unfamiliar," up to a value of "5" for "Extremely familiar." Correlation coefficients for all responses are shown below in Table 17, in which A13 corresponds to the responses to Question-13.

Table 17 Correlation coefficients for different responses to the questionnaire

	A1	*A2*	*A3*	*A4*	*A6*	*A8*	*A9*	*A10*	*A11*	*A12*	*A13*
A1											
A2	-0.238										
A3	-0.174	**0.749****									
A4	-0.183	0.354	0.480								
A6	-0.015	**0.536***	**0.669****	-0.043							
A8	-0.410	0.458	0.464	0.515	0.101						
A9	0.082	**0.603***	**0.584***	0.273	0.419	**0.647***					
A10	-0.179	0.440	**0.668****	**0.733****	0.027	**0.625***	0.527				
A11	-0.247	0.455	0.315	0.381	0.167	0.381	0.401	0.191			
A12	0.223	**0.587***	0.362	**0.724****	0.050	0.343	0.331	0.368	0.070		
A13	0.244	-0.174	0.329	0.481	0.071	0.282	0.043	0.416	-0.131	0.272	

* Significant at the level .05 (two-tailed) / ** Significant at the level .01 (two-tailed)

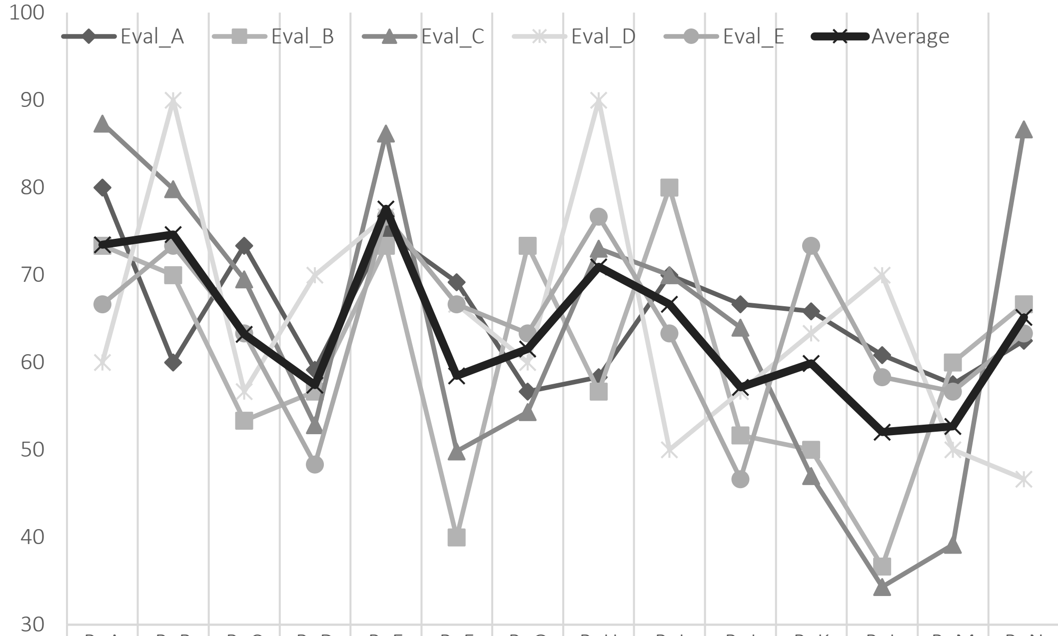
As shown in Table 17, positive correlations have been found between A2 and A3 ($r = .749$, $p < .01$), between A3 and A6 ($r = .669$, $p < .01$), between A3 and A10 ($r = .668$, $p < .01$), between A4 and A10 ($r = .733$, $p < .01$), and between A4 and A12 ($r = .724$, $p < .01$). The correlation between A2 and A3 can be interpreted as a tendency for a user to develop urban design concepts efficiently if the prototype is simple and easy enough to use. That is, the simplicity and easiness of the prototype may save the cognitive effort of those who made creative outcomes. The correlation between A3 (e.g., the prototype's effectiveness) and A6 (e.g., the design history navigation) can be explained from the responses to Question-6 and Question-7. Particularly, task participant N described that he could easily look up the records of design process history and figure out how to develop design ideas. He could move back and forth the different design concepts flexibly without freezing his memory for tracking. In this manner, the usability of design history navigation may increase the effectiveness of the prototype.

The correlation between A3 and A10 (satisfaction with the outcome) can be interpreted that the participants who developed design ideas efficiently could balance between convergent thinking and divergent thinking until they found a promising design idea. Efficiency during the design process may increase the opportunity to find satisfying ideas. The correlation between A4 (the provision of design alternatives) and A10 (his or her satisfaction with the outcome) is high. Presumedly, the participants were satisfied with the outcome if they could come up with an urban design result with an original idea with high quality. Even though there is a minority opinion of participant N, who views the provision of design alternatives in the prototype as limited in providing diverse ideas, therefore, as not helpful for developing design ideas better, but other participants made much importance of it. It is because the individuals could develop their design ideas better by reflecting on the ideas provided. The correlation between A4 and A12 can be explained that the use of analysis modules helps make informed decisions when it comes to evaluating uncertain ideas and saves cognitive overload for quantitative analysis.

Positive correlations have been found between A2 and A6 ($r = .536$, $p < .05$), between A2 and A9 ($r = .603$, $p < .05$), and between A2 and A12 ($r = .587$, $p < .05$). In particular, the correlation between A2 (simpleness and easiness of the prototype) and A6 (the use of design history navigation) can explain that it was not difficult and complicated to use the design history navigation of the prototype, similar to other operations. A positive correlation ($r = .584$, $p < .05$) has been found between A3 (efficiency of the prototype) and A9 (the level of proactiveness during the design process). If the prototype is not efficient to use, individuals would be disturbed and have less control over the design idea development progress. In this perspective, the correlation between A3 and A9 can be interpreted that the prototype's efficiency may help participants have more control over design development, which also helps them develop their concepts more proactively. A positive correlation that has been found between A8 and A10 ($r = .625$, $p < .05$) can be interpreted that a high level of being immersed in the design activity means that the participants could efficiently use their cognitive capacity for solving the design assignment given. As such, participants may come up with a design outcome with high quality, which can give satisfaction over the resulting design outcome.

7.3 Design Outcome Analysis

Five raters (i.e., Eval_A, Eval_B, Eval_C, Eval_D, and Eval_E) have evaluated the fourteen urban design outcomes (i.e., from ‘P_A’ to ‘P_N,’ where ‘P_A’ represents the design proposal of participant A) based on their expertise. The average age of the raters is 42 years, with a standard deviation of 1.67 years, and their average duration of service in the architectural field is 12.6 years, with a standard deviation of 3.3 years. The raters independently interpreted the urban design outcomes without trying to reach a consensus on the evaluation criteria; therefore, it is premature to find internal consistency, that is, how closely related a set of evaluation data are as a group. In such a case, arithmetic means of all scores are taken when evaluating creativeness scores of the urban design outcomes, which can be considered as a common decision-making method in practice.



	P_A	P_B	P_C	P_D	P_E	P_F	P_G	P_H	P_I	P_J	P_K	P_L	P_M	P_N
Eval_A	80.0	60.0	73.3	59.2	75.0	69.2	56.7	58.3	70.0	66.7	65.8	60.8	57.5	62.5
Eval_B	73.3	70.0	53.3	56.7	73.3	40.0	73.3	56.7	80.0	51.7	50.0	36.7	60.0	66.7
Eval_C	87.3	79.8	69.5	52.8	86.2	49.8	54.3	73.0	70.0	64.0	47.0	34.3	39.2	86.7
Eval_D	60.0	90.0	56.7	70.0	76.7	66.7	60.0	90.0	50.0	56.7	63.3	70.0	50.0	46.7
Eval_E	66.7	73.3	63.3	48.3	76.7	66.7	63.3	76.7	63.3	46.7	73.3	58.3	56.7	63.3
Average	73.5	74.6	63.2	57.4	77.6	58.5	61.5	70.9	66.7	57.1	59.9	52.0	52.7	65.2

Figure 73 Appropriateness scores of design outcomes

Overall appropriateness scores of the urban design outcomes are shown in Figure 73, of which the arithmetic mean is 63.6 with a standard deviation of 7.84. Urban design outcomes that receive a score above the arithmetic mean in appropriateness are ‘P_E,’ ‘P_B,’ ‘P_A,’ ‘P_H,’ ‘P_I,’ ‘P_N,’ and ‘P_C.’ They are clustered as a group of urban design outcomes that receive high appropriateness score than the arithmetic mean. In order to address the effect of the use of block variant generation and the use of block subdivisions on the design outcome, identified information is represented, as shown in Table 18.

Even if the number of blocks varies during the design process, the number of usages of block variant generation and the block subdivision tend to be related to the number of blocks in the design outcome that each participant proposes. Participants F and J used the block variant generation and block subdivisions exceptionally many times, but the variations of block typologies are not actually diverse. Participant E’s design outcome (i.e., ‘P_E’) received the highest score in appropriateness. Participant E mainly used the block variant generation and interactively transformed the selected block layouts further rather than just adapting the generated layout until favorable block layout ideas are achieved. Such a tendency can be found in the design process of other participants whose blocks in design outcomes are highly diverse in block layout configuration.

Table 18 Usage of block variant generation and block subdivision

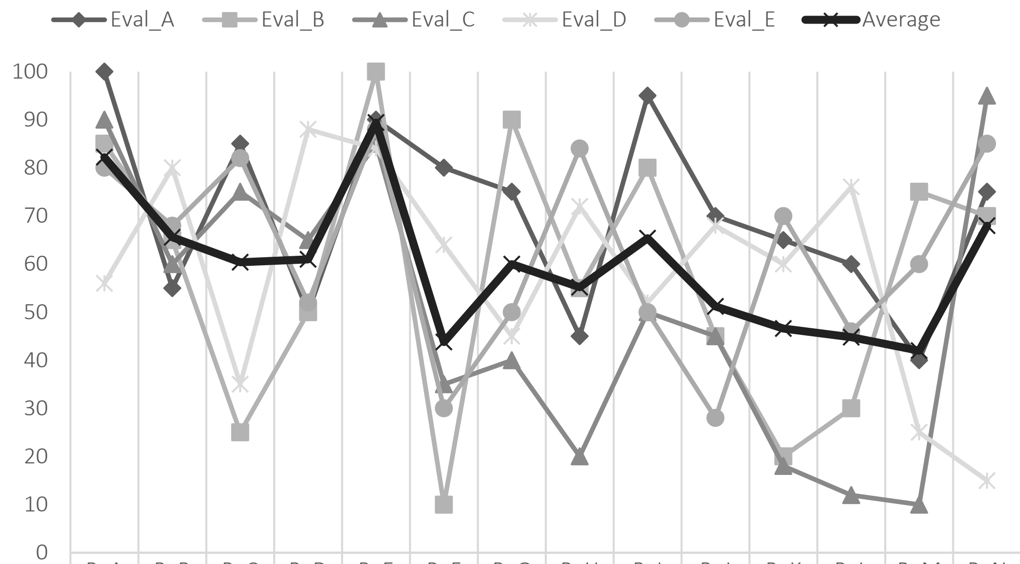
Group	Relatively high in appropriateness score							Relatively low in appropriateness score						
Ranking	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Outputs	P_E	P_B	P_A	P_H	P_I	P_N	P_C	P_G	P_K	P_F	P_D	P_J	P_M	P_L
Variant Generation	40	31	11	30	92	53	47	103	53	> 100[a]	54[b]	-	8	-
Subdivisions	-	-	80	-	-	-	17	-	-	-	-	60	36	52
No. of Blocks	43	50	136[c]	26	80	56	76	86	60	109[d]	69	12	43	46

a) Different block variants are a few; b) The function of block variant generation is used many times, but with a limited modification of the generated layout; c) During the idea development, the number of blocks steadily increased to 145 in the early design stage, then reduced to 137; d) The number of blocks is high, but similar block patterns are juxtaposed in parallel.

Among them, participant A is noticeable in the idea development process. First, the number of blocks generated in the final is remarkably high (i.e., 136 blocks). Participant A's approach is to divide the intervention site into minimum-sized blocks, then merge them to form a larger functional area. Except for relatively large, varied blocks, the block subdivision function is promptly applied instead of using the function for block variant generation. This is because participant A noticed that the suggested block layout from the use of design variant generation might not be diverse if the area size of the working block is small, and learned that the use of block subdivision based on gridiron system typology is enough to achieve diverse layout configurations.

Among those outcomes with a relatively low score in appropriateness, participants G, K, F, and D also used the automated block variant generation. The appropriateness score of Participant G's outcome (i.e., 'P_G') is close to the average. Nevertheless, I find P_G contains many diverse block configurations with a feasible idea. However, P_K, P_F, and P_D contain somewhat identical block layouts, which may not be enough to address the design issues that are requested to consider. Participant K, for instance, used it to search for somewhat identical block typologies; therefore, he spent less effort in searching for diverse ideas that can enhance design quality. Participant F used the block variant generation very often, but it was not to search for diverse ideas. Instead, it was to find a similar idea that Participant F had in mind from the start of the design experiment onwards. Participant F used the block variant generation more than a hundred times, the number of block layout patterns that are tested is only twenty-three, and only one of them is dominantly applied to the dwelling area. Participant D also used the function actively, but instead of developing varied block layout concepts based on the generated layout, minor modification is mostly applied to the selected layout. Participants J, M, and L used less the block variant generation. Instead, they conveniently applied the block subdivision methods depending on their favorable block typologies.

To summarize the discussion so far, ***participants with a high appropriateness score in their design outcome tend to use the block variant generation more frequently and interactively transform block layouts than the other participants with a low appropriateness score in their design outcome.***



	P_A	P_B	P_C	P_D	P_E	P_F	P_G	P_H	P_I	P_J	P_K	P_L	P_M	P_N
Eval_A	100	55	85	50	90	80	75	45	95	70	65	60	40	75
Eval_B	85	65	25	50	100	10	90	55	80	45	20	30	75	70
Eval_C	90	60	75	65	85	35	40	20	50	45	18	12	10	95
Eval_D	56	80	35	88	84	64	45	72	52	68	60	76	25	15
Eval_E	80	68	82	52	88	30	50	84	50	28	70	46	60	85
Average	82.2	65.6	60.4	61.0	89.4	43.8	60.0	55.2	65.4	51.2	46.6	44.8	42.0	68.0

Figure 74 Originality scores of design outcomes

Overall originality scores of the urban design outcomes are represented in Figure 74, of which the arithmetic mean is 59.7 with a standard deviation of 13.4. Urban design outcomes, of which originality score are above the arithmetic mean, consist of 'P_E,' 'P_A,' 'P_N,' 'P_B,' 'P_I,' 'P_D,' and 'P_C.' They are classified as a group of urban design outcomes that receive high originality score than the arithmetic mean of all originality scores. The backtrackings in the design history navigation are divided into two groups, depending on when the user recalls design ideas (i.e., in an early stage or later stage), as shown in Table 19.

As is in the appropriateness score, Participant E's design outcome (i.e., P_E) receives the highest score in originality. In total, three backtrackings are identified to be used in the development of

P_E. In the early stage, Participant E used backtracking twice to develop two competing ideas before selecting one favorable kernel idea for overall urban configuration and once for a detailed idea test in the later design stage. Once participant E was convinced of the selected urban configuration, more concrete ideas were gradually added and transformed using division and merge functions.

As discussed above, participant A generated many blocks quickly by using the block division and merge functions. Therefore, it was possible to juxtapose different layout units, which may increase the diversity of the design outcome. Participant N used backtracking three times through the design history navigation widget. Multiple layout ideas are tested in parallel and merge, dividing, and superimposition are interactively applied for transforming layout ideas. Participants B and G are somewhat similar in the use of design history navigation. They both use it in a later stage once the main idea is set. Without transforming the overall design concept, varied building layouts in the block level are tested using the backtracking function. Before the idea development of P_H, Participant H developed a different urban idea, for which development the design history navigation was used two times. However, this idea was discarded in favor of the concept idea that will lead to the design outcome, P_H.

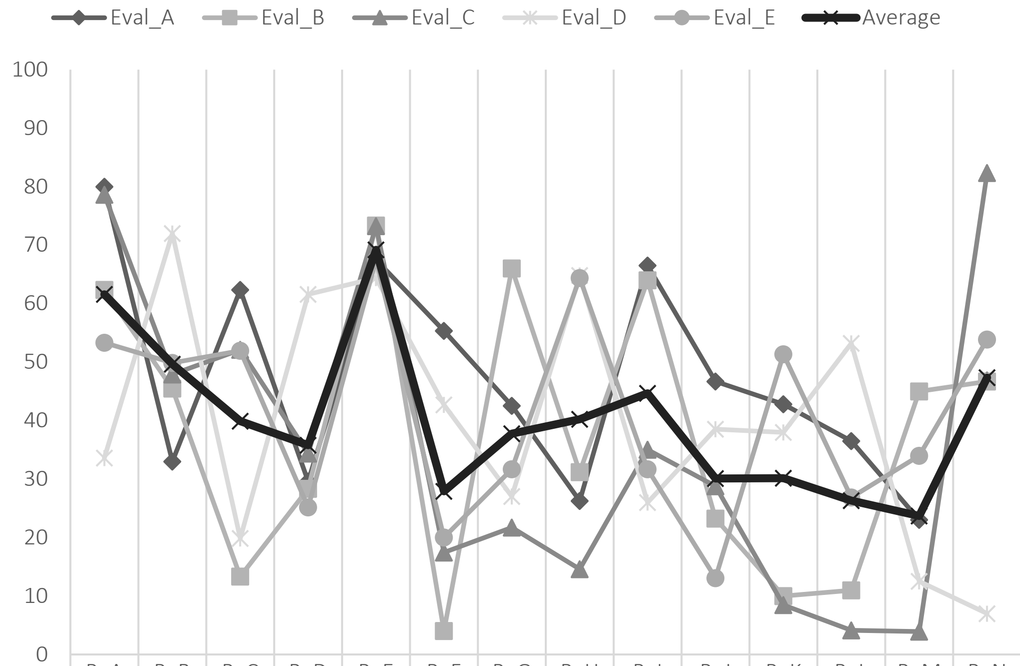
Table 19 Participants' use of the design history navigation

	Ideas high in originality score							Ideas low in originality score						
Ranking	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Outputs	P_E	P_A	P_N	P_B	P_I	P_D	P_C	P_G	P_H	P_J	P_K	P_L	P_F	P_M
Early-stage	2	-	3	-	14	1	1	-	-	1[e]	1	-	1	-
Later-stage	1	-	-	4	-	-	-	3	2	-	-	-	-	-
Sum	3	0	3	4	14[f]	1	1	3	2	1	1	0	1	0

e) A back-tracking is used once for the minor transformation of the previous idea; f) Multiple layout ideas are tested before choosing one central idea of the site.

Participants D, C, J, K, and F used design history navigation for backtracking, respectively. Among them, Participant J used it for the minor modification of former ideas instead of developing a new urban configuration concept. Participants L and M did not use it for backtracking at all. The frequent use of backtrackings is noticeable while P_I was developed. Participant I used it fourteen times to test different ideas before deciding the main idea of the site. However, just because the ideas that were tested using backtracking are many, it does not mean that ideas are diverse. Participant I continued to keep design ideas together within the control limits and tested them until a favorable one is selected.

To summarize the discussion so far, ***results show that the effective use of design history navigation in the early design stage tends to be helpful to develop diverse original ideas.*** The capacity for navigating ideas that are examined in different design sessions can help human designers keep varied ideas together, unburden the effort to keep ideas. Moreover, the interaction with the design support may stimulate human designers to explore unexplored ideas.



	P_A	P_B	P_C	P_D	P_E	P_F	P_G	P_H	P_I	P_J	P_K	P_L	P_M	P_N
Eval_A	80.0	33.0	62.3	29.6	67.5	55.3	42.5	26.3	66.5	46.7	42.8	36.5	23.0	46.9
Eval_B	62.3	45.5	13.3	28.3	73.3	4.0	66.0	31.2	64.0	23.3	10.0	11.0	45.0	46.7
Eval_C	78.6	47.9	52.1	34.3	73.2	17.4	21.7	14.6	35.0	28.8	8.5	4.1	3.9	82.3
Eval_D	33.6	72.0	19.8	61.6	64.4	42.7	27.0	64.8	26.0	38.5	38.0	53.2	12.5	7.0
Eval_E	53.3	49.9	51.9	25.1	67.5	20.0	31.7	64.4	31.7	13.1	51.3	26.8	34.0	53.8
Average	61.6	49.7	39.9	35.8	69.2	27.9	37.8	40.2	44.6	30.1	30.1	26.3	23.7	47.3

Figure 75 Creativeness scores of design outcomes

A creativeness score of a design outcome is calculated by multiplying its average appropriateness scores and average originality scores. Final creativeness scores of the urban design outcomes are visualized in Figure 75, of which the arithmetic mean is 40.1, with a standard deviation of 12.6. Urban design outcomes above the arithmetic mean of all creativeness scores are ‘P_E,’ ‘P_A,’ ‘P_B,’ ‘P_N,’ ‘P_I,’ ‘P_H,’ and ‘P_C’ from high to low in descending order. Except for the design outcome ‘P_A,’ the design outcomes with high scores both in appropriateness and originality are ‘P_E,’ ‘P_B,’ ‘P_C,’ ‘P_I,’ and ‘P_N.’ Until obtaining such design outcomes, it is identified that participants B, C, I, and N tend to actively use both the block variant generation and the design history navigation for idea backtracking.

7.4 Design Experiment Analysis Summary

This chapter presented the analysis of participants’ responses to the questionnaire and the implications by identifying the correlations between the responses to different aspects of the prototype used in the design experiment. Furthermore, the experts' evaluations of the design outcomes by applying creativity metric are discussed in relation to the use of the design support prototype. Nevertheless, it is limited in accurately evaluating how the proposed interactive urban design methodology can encourage a human designer to find urban design ideas effectively. The number of samples is fourteen, which may be considered not enough for drawing a solid scientific conclusion.

Nevertheless, important implications can be found from the participants' responses to the questionnaire. It is identified that the participants seem to accept the use of urban design support prototype helpful for developing their own ideas efficiently. They find the provision of design alternatives and the use of design history navigation in the design support prototype helpful to develop design ideas. Also, they could develop their own design ideas proactively while being immersed during the design process.

Regarding the evaluation of design outcomes, even though the exceptional case among test participants exists and more samples through the design experiment should be required to draw a more clear explanation, it is identified that both the use of the generation of design alternatives and design history navigation significantly affects the urban design outcomes. For design outcomes with relatively high appropriateness scores, participants tend to use the function for block variant generation efficiently. Until obtaining design outcomes that are high in both appropriateness and originality, it is evident that participants tend to actively use both the block variant generation and the design history navigation for idea backtracking.

Therefore, I conclude that the hypothesis *"The proposed interactive design approach can encourage a human designer to find urban design ideas effectively"* is valid by two sub-hypotheses, which are accepted in Subsection 7.3. This is supported by findings that the design with the support of design history navigation will help find unique design ideas, which enhance design creativity, and that the design with the support of the design variant generation will produce a higher quality design. This design experiment results provide greater insight into the design support, specifically on how the use and incorporation of the interactive urban design exploration affect the quality and creativeness of design outcomes during the conceptual design stage.

8 Conclusion

Generative approaches to urban design synthesis have been proposed to address various urban design tasks, as discussed in 2.4. These approaches aim to support the human designer by synthesizing numerous design solutions during conceptual and detailing design stages. In most generative design approaches, problem-specific design knowledge must be formulated formally, and the generative rules that describe design transformations are repeated for obtaining design alternatives. While these generative approaches have many advantages for synthesizing familiar or somewhat creative design ideas, their application in industry and academia is not yet widely spread for various reasons (Daniel Davis, 2020). One reason is that even the co-evolution of the problem and solution spaces in Subsection 2.1.2 is an important aspect of creative design, all generative tools that have been known so far are not really capable of supporting this aspect. Moreover, human designers cannot work with the generative approaches flexibly enough for practical applications in developing urban design solutions. Often certain design issues that are required for developing urban design solutions cannot be integrated into the support tool or rules. This is a common limitation of all-known generative approaches or AI-based tools for urban design synthesis, which is discussed extensively in Sections 2.4 and 2.5.

This research aims to help human designers overcome some of the challenges in applying generative urban design approaches. Being aware of how human designers think and perceive enables advanced design support methodology that systematically helps them search for appropriate or even creative design concepts for urban design problems. The interactive generative design approach's ultimate goal is to enable human designers to explore creative urban designs.

8.1 Summary

Three aspects for the improvement of the urban design support methodology should be highlighted: naturalistic design generation and transformation operations, suggesting multiple alternatives for a particular design problem, and managing the design history. First, more CAD operations for supporting naturalistic cognitive thinking should be provided for human designers to develop urban design ideas interactively. The lack of interactive design support in idea development is a major drawback of generative approaches, arguably increasing cognitive overload. Second, design support for suggesting multiple alternatives to a particular urban design problem should be provided to improve creative thinking. Being supported with the utility and the divide-and-merge operation enable human designers to explore varied design ideas in different levels of detail. Third, support should be provided for managing design history. This includes supporting human designers in navigating different design sessions and reusing them to synthesizing new design ideas. This is somewhat novel in that the design support allows the human designer to lead the idea development proactively.

To test the research hypothesis, "*The proposed interactive design approach can encourage a human designer to find urban design ideas effectively*," this dissertation is structured as follows:

Chapter 2 provided an extensive review of designers' approaches to problem-solving and design creativity issues to support the conceptual design for urban master-planning. Rule-based computational approaches to urban design are discussed to support human designers using interactive urban layout generation methods. I provided a summary of recent applications and urban layout generators and discussed challenges for urban layout rule development and application are identified.

Chapter 3 prescribed the methodology for supporting rule-based urban form synthesis. For this, a generic framework is proposed to support the interactive exploration of urban design. The fundamental rules that enable the synthesis of several representative urban fabrics are introduced in detail. The available options for urban generation, analysis, and data visualization, as well as possible user interactions, are presented as well.

Chapter 4 prescribed strategies to interact with the urban design support and explore different urban design variants. The generation and visualization of urban design variants allow the human designer to compare the generated variants intuitively. These supports can lead to fast decision-making by the convergence of the quantitative and qualitative evaluation simultaneously. Besides, understanding how strategies for navigating design episodes that are generated at each sequence of design steps allows the human designer to select an appropriate one for a given urban design task more flexibly.

Chapter 5 provided the three case studies to show to what extent human designers can use the developed urban design support prototype to realize different urban design tasks. The methods implemented in the prescribed computational urban design support prototype have successfully been validated using case studies for interactive urban design exploration. The three case studies demonstrate how urban design concepts are developed using the presented methodology, which supports the human designer during conceptual urban design by synthesizing numerous block designs and navigating different design sessions.

Chapter 6 presented the design experiment method to verify the prescribed methodology. For evaluating design outcomes, a measurement metric for creativity and evaluation procedure by experts was presented.

Chapter 7 provided the analysis of the questionnaire and the evaluation of participants' design outcomes from the experiment and discussed the significance of such results, considering the research questions and hypothesis.

Based on the analyses of design experiment results, it is concluded that the hypothesis "*The proposed interactive design approach can encourage a human designer to find urban design ideas effectively*" is valid, which is supported by two accepted sub-hypotheses in Subsection 7.3.

8.2 Research Contributions

Recent computational tools, as discussed in Section 2.4, have been proposed to support urban design, but the human designers' cognitive processes, which are central in developing new design ideas, are rarely taken into consideration in the research and development of urban design support. Several computational approaches have been developed to address decision-making for the generation, evaluation, and selection of urban design alternatives. The support of such approaches includes partial/full automation of design tasks or even the augmentation of the designers' mental activities, therefore, impact the efficiency and effectiveness of design exploration. However, there are fundamental human characteristics that cannot currently be implemented within computational environments (Lawson and Dorst, 2009). Such human aspects include naturalistic decision-making relying on designers' experience and instincts, interpreting design situations (Gero, 1994).

This research makes a meaningful contribution to address the preliminary overarching research question, *"How can the human designer be supported efficiently for the idea generation in an early urban design stage?."* The challenge of the proposed computational urban design methodology is supporting designers' actions within the larger systems of interactions. The concept of interactive urban design exploration for naturalistic breadth-first and depth-first searches at the urban district level is implemented in the design history management module. Through navigating the design history, designers can save a considerable amount of time and effort attempting to recall their previous works. The proposed computational urban design support can support changes in the topology of urban design entities. Such an approach allows for relating parts to the whole and vice versa, which is a fundamental operation that designers apply to solve urban design problems. Also, performing rapid evaluations can be supported when partial updates of design entities are detected. When a designer triggers merging or dividing operations into design entities, the design support can calculate only the area on which the updated design entities belong. Such a strategy can support the designer's actions by preventing the delay from computing the overall area.

The generation of design alternatives is based on the rule-based, parameterized approach so that designers can test and develop diverse alternatives. The design rule is implemented based on the analysis of popular land typologies such as perimeter block or land division. Depending on the design requirements, constraints, and norms, designers can immediately test and adopt satisficing design styles that fit into the intervention entities. Moreover, designers can directly modify the generated design by applying basic operations such as merging and dividing the design entities. By automating the generation of design alternatives and allowing for direct control of the generated design, the proposed computational design support methods can promote design exploration efficiency and effectiveness and test more diverse design solutions.

Multiple design alternatives can simultaneously be generated and visualized to the human designer, which can contribute to enhanced decision-making. Instead of presenting alternatives one by one, such an approach allows for comparing design alternatives concurrently from quantifiable and non-quantifiable aspects. The newly generated alternatives can be used to compare and judge the design in the designer's mind, or they can stimulate the designers to generate new designs that are not like the preexisting examples.

This research has demonstrated the use of the interactive prototype for urban design exploration. It concludes that the design approach with effective variant generation and history management obviously holds many advantages over other automated generative design methods with which human designers can hardly interact. For example, formulating all problem spaces and their matching solution spaces on the onset is not a trivial task in many design cases. Conceptual design is a creative process in which designers co-evolve both problem space and solution space by creating functions to satisfy requirements and form and structure to fulfill the requirements.

8.3 Limitations and Future Works

I could identify a few limitations of the implemented design support based on a posterior discussion with test participants. The provision of design alternatives and the reuse of design episodes by back-tracking of design history should be further elaborated. For example, current block design alternatives are generated using a layout generation algorithm that lacks semantic information. I find such a limitation can be supplemented by the application of a case-based design approach at an urban scale. Existing methods for calculating the similarity between urban structures should be further developed to generate new urban design solutions that address the problems of the working area. Still, there is a limitation in representing design alternatives when the design support prototype is used to generate them. This is related to the formal representation of problem-specific urban design knowledge and the description of design transformation rules, which can steer the creative design synthesis process.

Many improvements are possible, of which the most obvious ones include undo-redo features that most participants wish to use during design experiment sessions. This can be implemented by expanding the module of design history management. Other possible extensions can include drawing features such as curved shapes, which are not supported. The calculation of the distance between building volumes and plots should be implemented to support decision-making in consideration of building code and zone ordinance. The not yet integrated module for daylight analysis can be extended by connecting with geographic data available openly. However, additional GIS data of the surrounding area needs to be supplemented to improve the precision of analyses.

Moreover, I find a few limitations in the evaluation of the proposed design approach through the laboratory setting. For this research, it was not avoidable to conduct the design experiment for a relatively short duration. It is worth testing the proposed approach in a relatively long-term period and identifying further aspects for effective design information management and design support, which enable designers to more fully explore the design space. Moreover, it is identified that those test participants found the size of the urban design task somewhat large; therefore, they might be limited for testing varied ideas.

Instead of a single designer, how multiple designers in a collaborative design environment can interact with the proposed approach needs to be investigated. Such research has the potential to help further improving the design support methods for urban design. The implemented design support prototype does not support the navigation of multi-level design sessions; elaborating the widget interface for the design history is necessary. A method to perceive the human designer's intention based on user operation should be supported, which may systematically detect cognitive pitfalls, such as circumscribed thinking, premature fixation, bounded ideation (Robertson and Radcliffe, 2009) and take actions for creative thinking.

However, it should be more discreet in making extensions into the prototype. This is because it is identified that the strength of the proposed approach using the urban design prototype lies in its simplicity. Additional extensions may interfere with helping human designers' creative thinking. I advocate that too much automation in the early design stage can work against pursuing creative ideas, and complications induced by adding less necessitated functionality into the user interface can hinder the intuitive operation.

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Appendix

Glossary

Search	A process of locating values of variables in defined state space (Gero, 1994, p. 315).
Breadth-first design	A process of developing an integrated solution at one level of detail for all subparts of the problem before moving onto a new level of detail (Ball and Ormerod, 1995, p. 134).
Depth-first design	A process of developing one sub-part of the problem at a time through progressive levels of detail (Ball and Ormerod, 1995, p. 134).
Top-down design approach	The overall scheme of the system is designed first; then, the system is progressively decomposed into subsystems, which are refined at increasingly greater levels of detail, sometimes in many additional subsystem levels (Guindon, 1990a, p. 309).
Bottom-up design approach	Contrary to the top-down design approach, elementary modules are specified first; then, they are combined into a larger one. For example, for urban design by Duarte and Beirão (2011), the urban units are defined first; then, the street network is defined as a result of the recursive addition of block arrangements.
Alternative	One of two or more available possibilities (Oxford Dictionary).
Variant	A form or version of something that differs in some respect from other forms of the same thing or from a standard (Oxford Dictionary).
Abstraction (Disambiguation)	A process of removing detail from a complex design situation and reducing it to a set of necessary design features (Simon, 1973, p. 195).
Design features	Design aspects or variables such as width, height, length, etc.
Design states	Representations of a design at a specific moment in time.
Design space	When a problem is given, design space is all possible options for the problem
Exploration	A process for creating new design state spaces or modifying existing design state spaces. (Gero, 1994, p. 315)
Generative design	A design method applies iterative rules for geometric or topological transformations (Bernal, Haymaker, and Eastman, 2015, p. 170).

Parametric design	A design method represents geometric relationships of design entities in a hierarchical data structure and automatically updating and visualizing design when changes in values of the parameters occur (Kalay, 1989).
Protocol analysis	A widely used method for understanding designers' thinking, for example, by analyzing the transcribed verbal record based on a pre-defined coding scheme (Ericsson and Simon, 1999)
Rule-based design	A design method evaluates the design outcome based on the level of fulfillment of design rules and providing feedback regarding conflicts. The design rules can include constraints, requirements, guidelines, or conditions (Eastman *et al.*, 2009, p. 1012).
Convergent thinking	A kind of cognitive style that is primarily concerned with taking in information and producing a single correct answer to a problem (Cross, 1985, p. 158).
Divergent thinking	Contrary to convergent thinking, it is the cognitive phase that a person generates a wide range of answers, which are diverse in range (Cross, 1985, p. 158).

Outputs from the Design Experiment

Areas	Color codes
Dwelling area	
Open area	
Water area	
Commercial area	
Education area	
Sports area	
Green area	

Participant A

Figure A-1 A screenshot of participant A's proposal for Lerchenauer Strasse

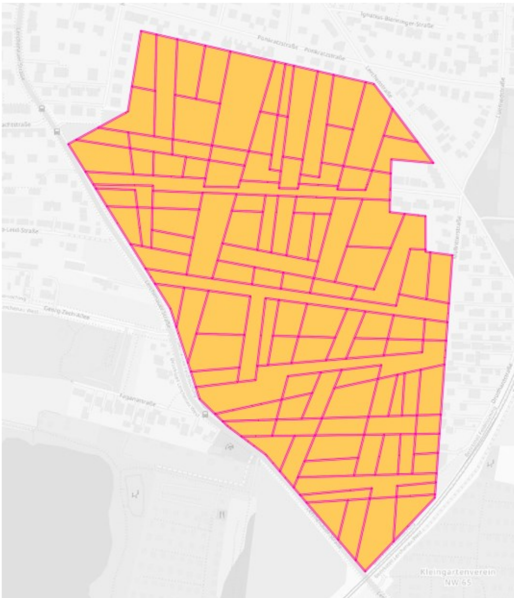
(1) A final urban design outcome

(2) Plot distribution

(3) Plot allocation based on the zoning

(4) Zoning

Figure A-2 Urban patterns of the final urban design outcome by Participant A



(1) Design session 1: Initial road network and block division are tested

(2) Design session 2: Additional block division and initial zoning are tested

(3) Design session 3: Minor block modification and initial plot division are practiced

(4) Design session 4: The generation of the different building with various layout typology

Figure A-3 Snapshots of design progress until reaching the final design outcome

Overall, participant A tried to allocate water area and open space in consideration of the district area's openness and used divide-and-merge operations effectively. However, the use of design history navigation is limited because participant A's central concept about this project is decided in early time and is not changed only with minor modifications in the block level. For the plot allocation, participant A used the function of the alternative generation and found it useful. Participant A used the function of alternative generation 11 times, about 1 hour 3 minutes in total, and spent relatively much time considering a block's scheme when the blocks have irregular shapes.

When participant A thinks that the open space is relatively scarce near the old town, participant A decided to allocate open spaces near the intervention site's boundary. The commercial areas are intensively allocated near the northwest and southeast area. The education facility is put on near old towns to balance the development of the new town and old town. After defining the main functions of blocks, participant A decided to subdivide larger blocks or extended areas into smaller ones and then change some of the blocks' functions to open space and water park. Building insertion and delete buildings are performed to allocate an open area in each block level.

Participant B

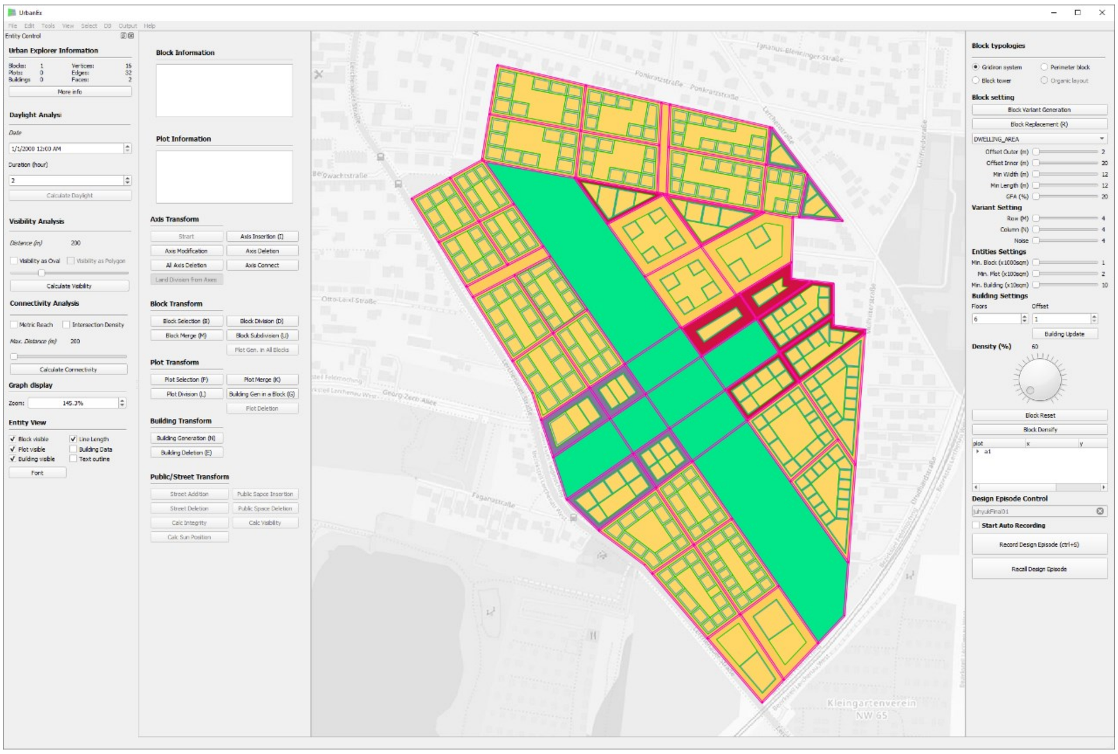
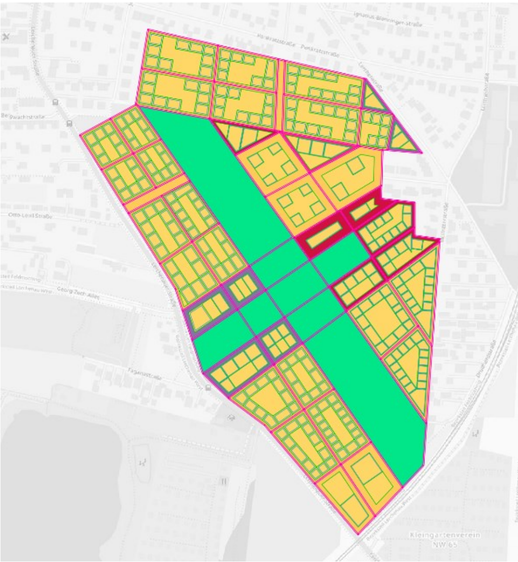
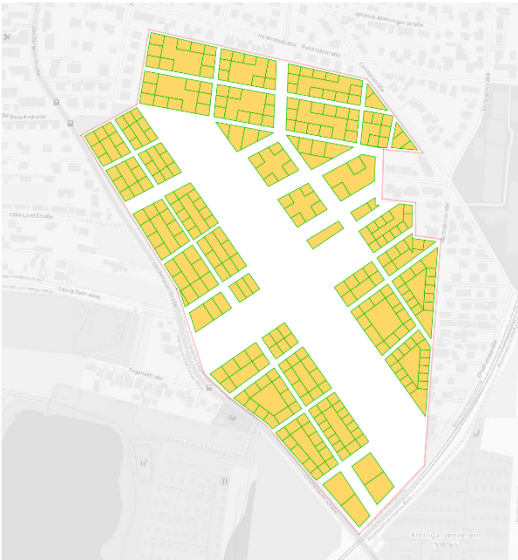


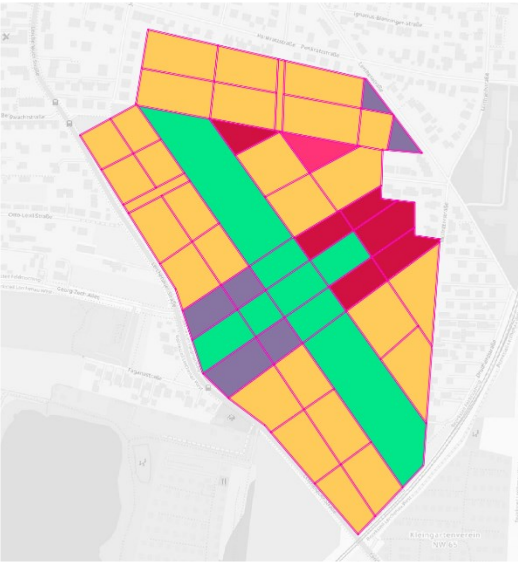
Figure B-1 A screenshot of participant B's proposal for Lerchenauer Strasse



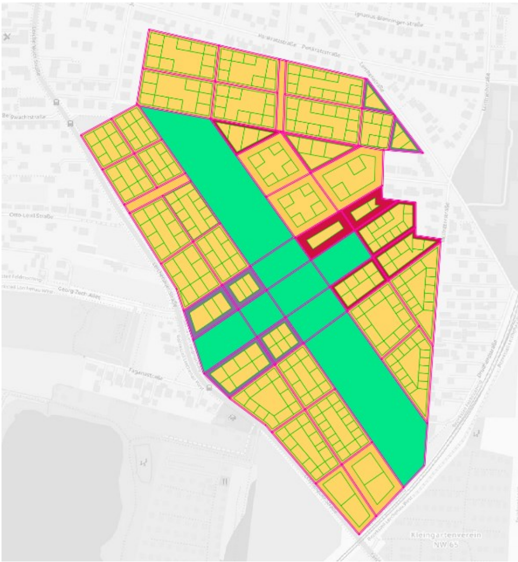
(1) A final urban design outcome



(2) Plot distribution



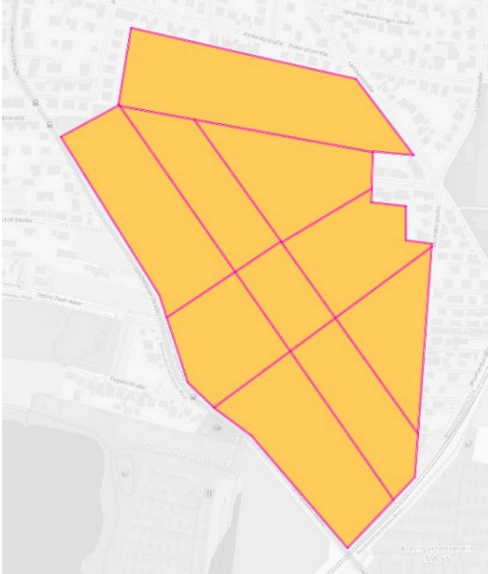
(3) Zoning



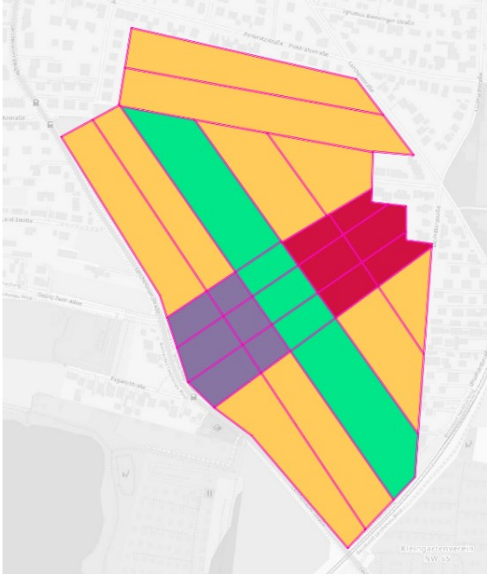
(4) Plot allocation based on the zoning

Figure B-2 Urban patterns of the final urban design outcome by participant B

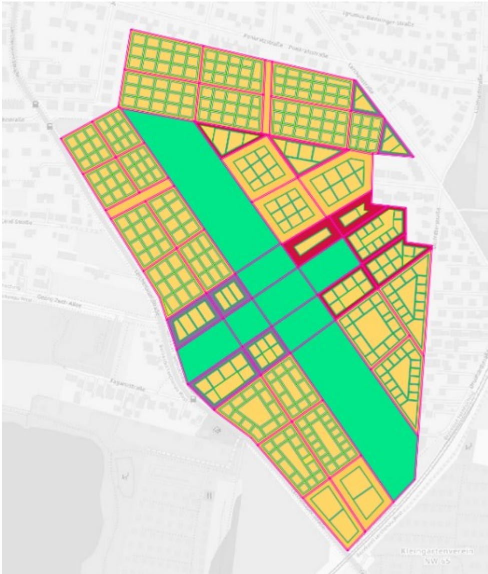
Participant B considered efficient transportation circulation and pleasant greenfield inside the intervention site. After the initial analysis, the site is identified as irregular, which faces diagonal roads and railroads in the south and housings in the north. So, participant B proposed organic zoning and building design that can connect north and south, suggesting a new urban context. To emphasize the movement and flow in urban scale, the green axis that penetrates the whole site is introduced; after that, diverse space programs are arranged accordingly, which leads to efficient pedestrian flow for dwellers who live in the surrounding areas. Furthermore, social mixing can be expected through the arrangement of community facilities. Various housing types that are arranged along the green axis consider sunlight. High-rise buildings are allocated near the main street and greenfield, and middle/low-rise buildings have their own inner courtyards, which may define spatial relations that connect public, private, and semi-public areas.



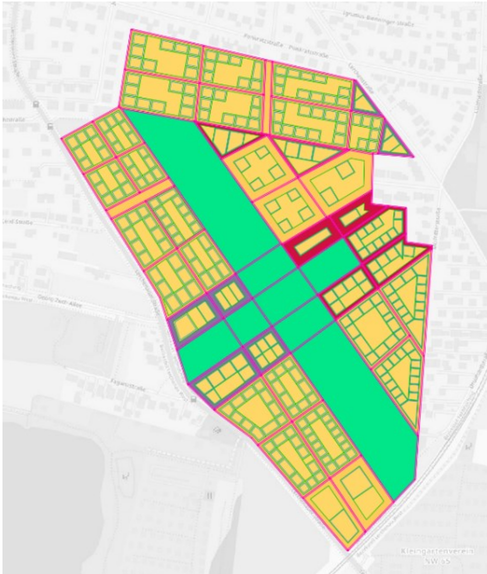
Design session 1: Initial axes



Design session 2: further division of the site considering zoning



Design session 3: Plot generation considering zoning



Design session 4: Block configuration and building allocation

Figure B-3 Snapshots of design progress until reaching the final design outcome

In consideration of the right to sunlight, the distance between block volume and height is controlled. In design session 1, analysis of existing urban form and structure is conducted; thereafter, main axes are drawn according to incident roads and railroads, which aim to connect to the existing transportation system. In design session 2, greenfield, commercial, and educational areas are defined in the site's central area. In relation to the greenfield, different types of housings are allocated, which can achieve an organic spatial structure that links to their surroundings. In design session 3, while designing various housing types, participant B tries to maximize the density of the site while emphasizing the connection to the greenfield. In design session 4, multiple studies are conducted to define various housing types in consideration of sunlight, an inner buffer zone for privacy, and green space.

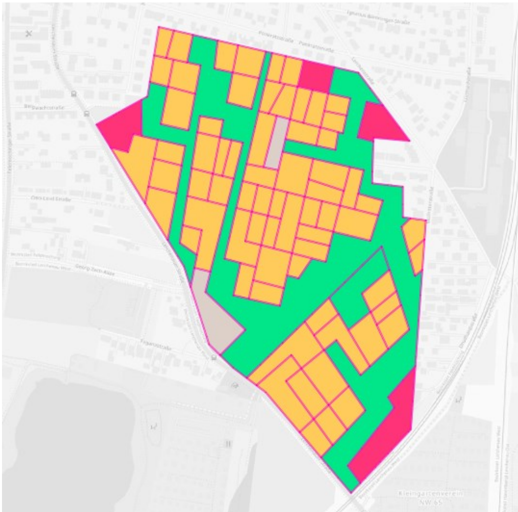
Participant C

Figure C-1 A screenshot of participant C's proposal for Lerchenauer Strasse

(1) A final urban design outcome

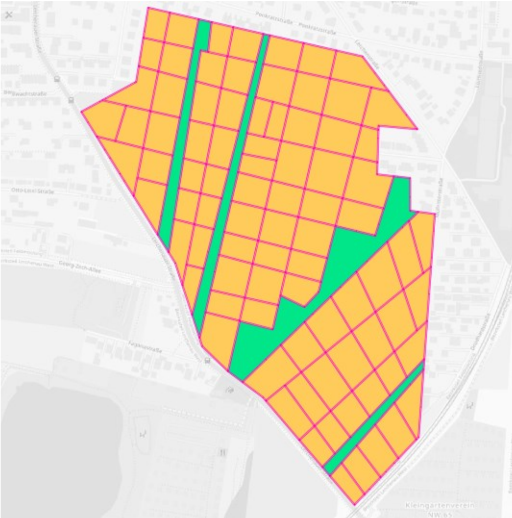
(2) Plot and building distribution

(3) Plot allocation based on the zoning

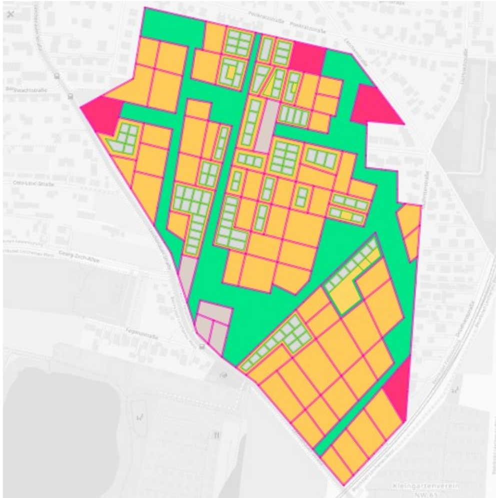


(4) Zoning

Figure C-2 Urban patterns of the final urban design outcome by participant C



(1) Design session 1: Initial road network and block division



(2) Design session 2: Additional block division and initial zoning with plot generation

(3) Design session 3: Minor block modification and plot division

(4) Design session 4: The generation of the different buildings with various layout typology

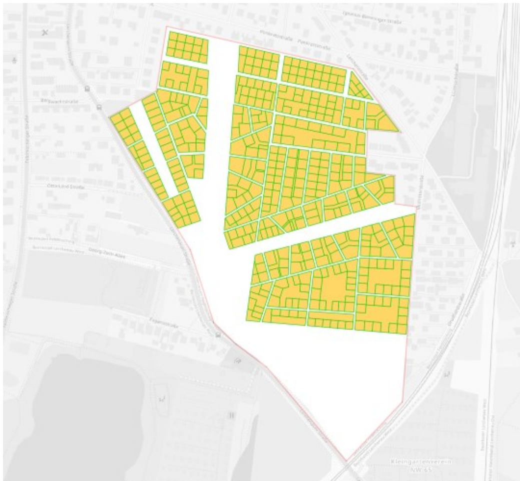
Figure C-3 Snapshots of design progress until reaching the final design outcome

Initially, participant C tries to make a grid pattern that orients toward the lake; after that, participant C makes smaller grids, which are merged to make several green corridors. The green corridors are linked all together to make a continuous green network, by which it is intended for people to be able to walk without barriers. During idea generation, participant C seems not to be fixed to the initial idea; instead, she flexibly transformed many local areas, by which she achieves diverse blocks that vary in size from small to middle. When the bounding shape of blocks is irregular, participant C uses the block variant generation often. Later, participant C finds the horizontal lines are unsuitable for the site; therefore, she adapted diagonal dividing lines that point to the lake in the southwest. More lines are added, which are perpendicular to the diagonal lines, in order to make blocks in a manageable size. Participant C repeated divide-and-merge operations to develop blocks and make shallow three blocks that are directing to the lake are made for open space. The layout of the final design is hybrid, where grid and radial patterns co-exist. The duration of idea development is 1:33.

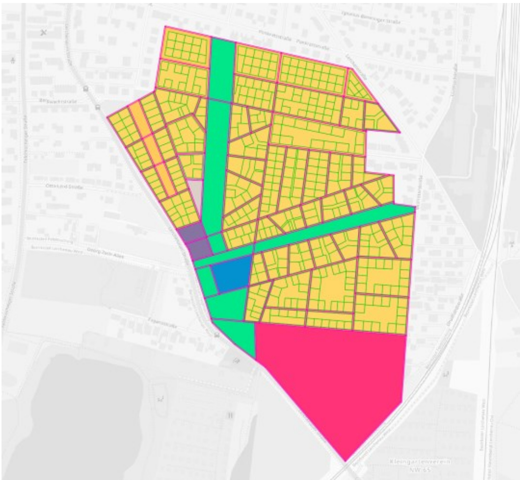
Participant D

Figure D-1 A screenshot of participant D's proposal for Lerchenauer Strasse

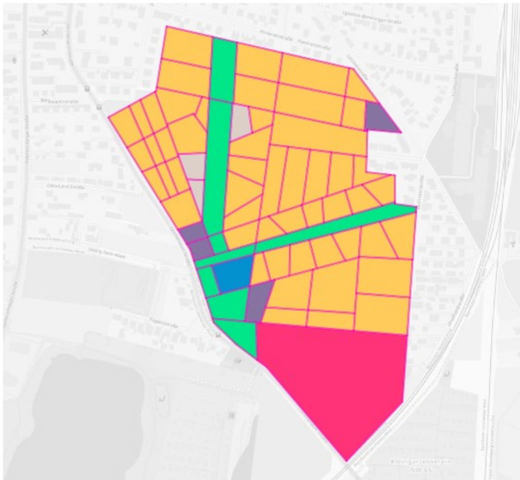
(1) A final urban design outcome



(2) Plot distribution

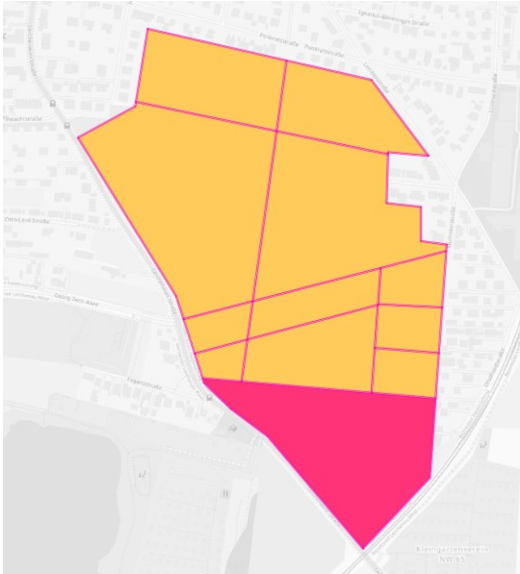


(3) Plot allocation based on the zoning

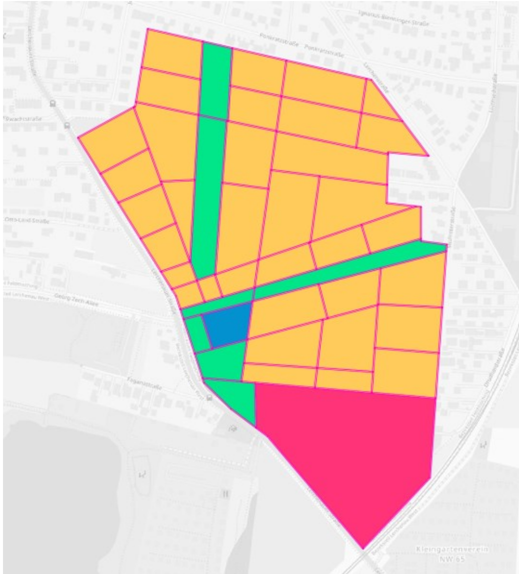


(4) Zoning

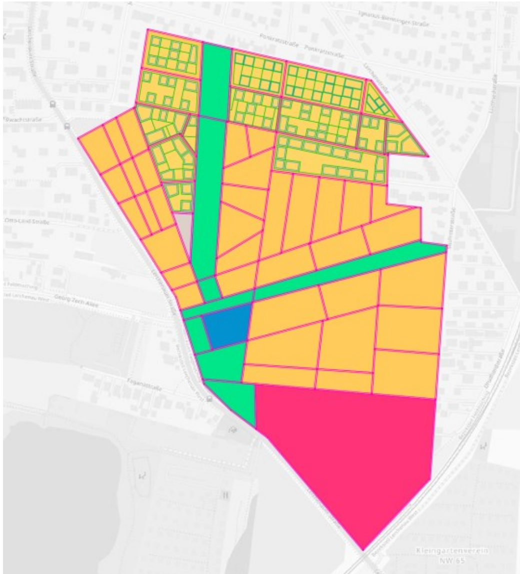
Figure D-2 Urban patterns of the final urban design outcome by participant D



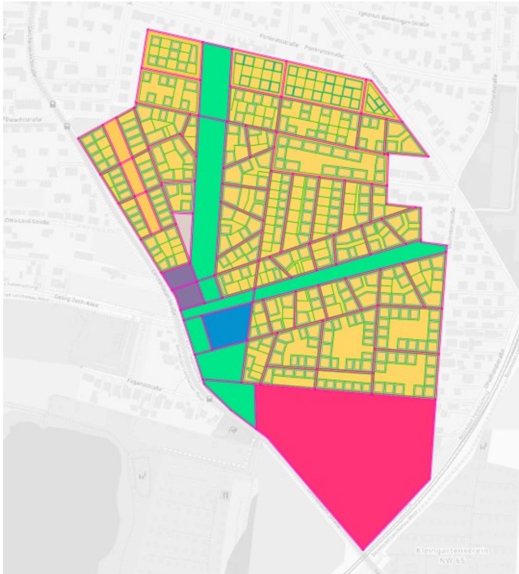
(1) Design session 1: Initial main road network and block division



(2) Design session 2: Additional block division and initial zoning



(3) Design session 3: Minor block modification and initial plot division



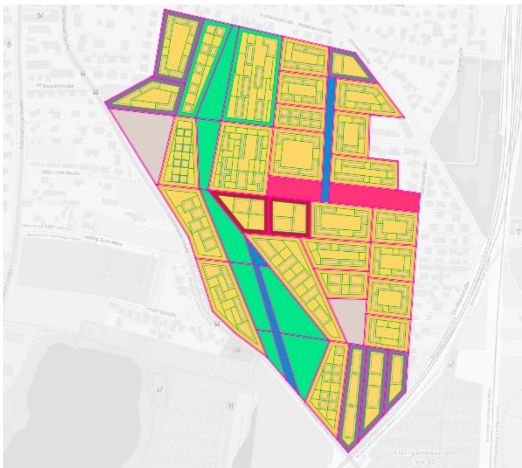
(4) Design session 4: The generation of the different buildings with various layout typology

Figure D-3 Snapshots of design progress until reaching the final design outcome

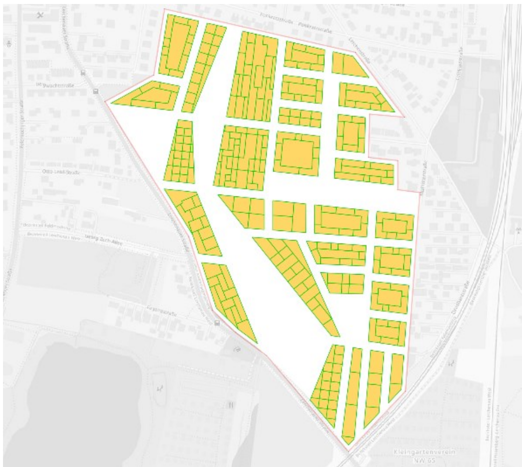
Participant D allocates a large sports area in the southern part of the site and draws a line axis from the station to the lake to make the main passage. Moreover, another axis that connects the northern area is introduced, which becomes a greenery area. In northern parts, block typologies are based on the gridiron, which resembles an existing block configuration. Furthermore, the rest area adapts perimeter block housing typology. Participant D tries to realize a rather organic pedestrian flow by linking voids between blocks when transforming blocks with perimeter block housings near green areas. In the midwestern part of the site, commercials, water, and open areas are allocated to function as a keyspace. The duration of idea development is 1:17.

Participant E

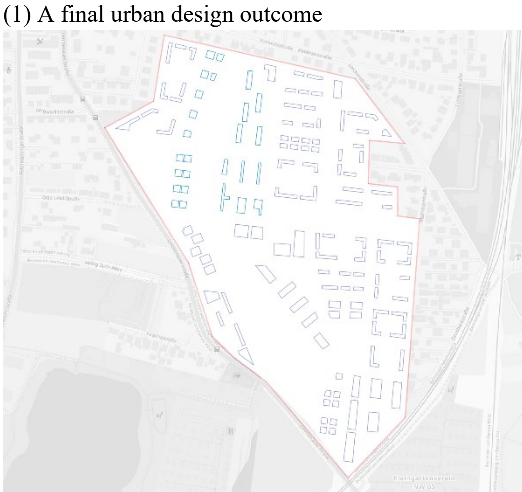
Figure E-1 A screenshot of participant E’s proposal for Lerchenauer Strasse



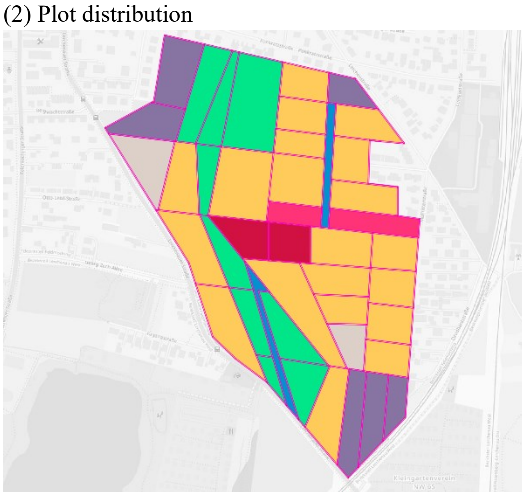
(1) A final urban design outcome



(2) Plot distribution

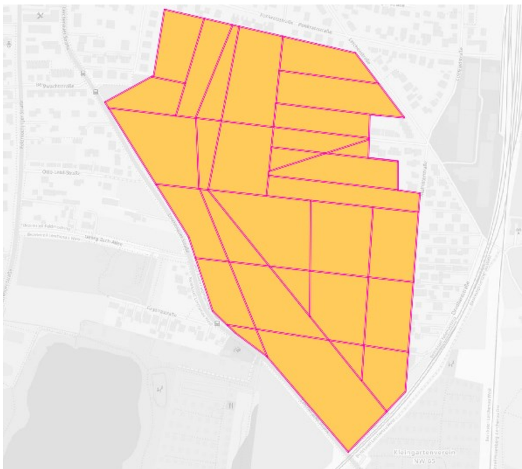


(3) Building allocation

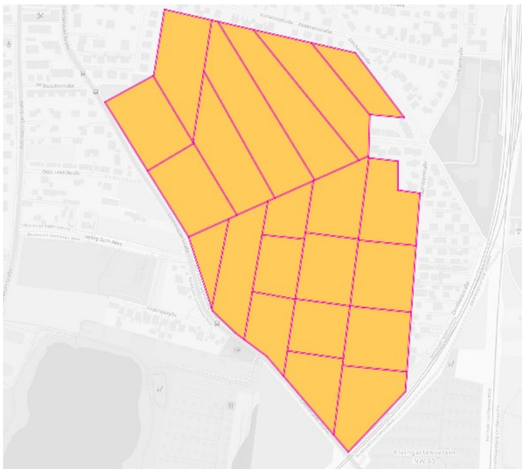


(4) Zoning

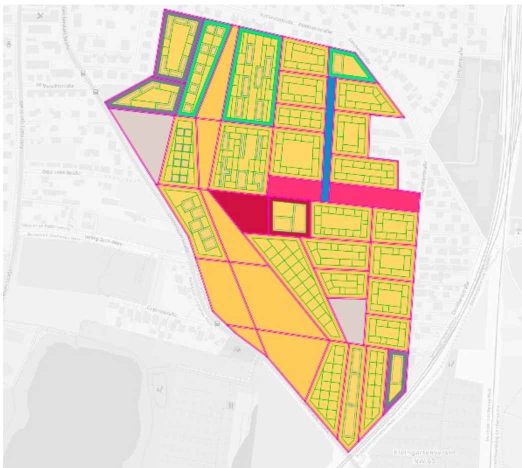
Figure E-2 Urban patterns of the final urban design outcome by participant E



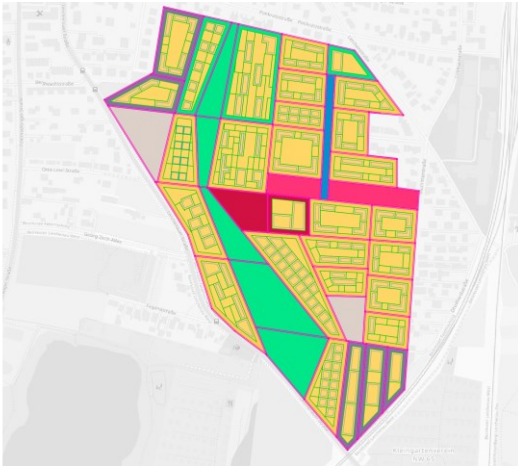
(1) Design session 1: Initial road network and block division



(2) Design session 2: Testing different urban layout



(3) Design session 3: Minor block modification and initial plot division using the idea in design session 1



(4) Design session 4: The generation of the different buildings with various layout typology

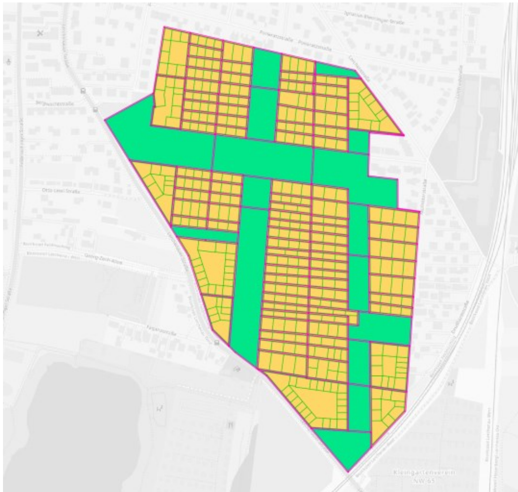
Figure E-3 Snapshots of design progress until reaching the final design outcome

Participant E tries to decide the area for the greenfield in the intervention site. Axis lines from the northern area to the south were tried, as shown in design session one in Figure E-2. Thereafter, as shown in the image shot in design session two in Figure E-3, another concept was tested, which is not continued to be developed. The idea of design session one was recalled and further developed. The Green area is defined by a vertical axis and has variations in width. Education facilities and open space are placed in the central area, which is mixed with sports facilities. Mainly perimeter blocks are favored in housing areas, and free-standing buildings are favored in commercial and other types of blocks. The skyline is somewhat diverse. Along the green area, high buildings with ten stories are allocated, and the stories of buildings in the commercial areas, which are on the corners of the intervention site, are 12-15. Housings are suggested less than five stories.

Participant F

Figure F-1 A screenshot of participant F’s proposal for Lerchenauer Strasse

(1) A final urban design outcome

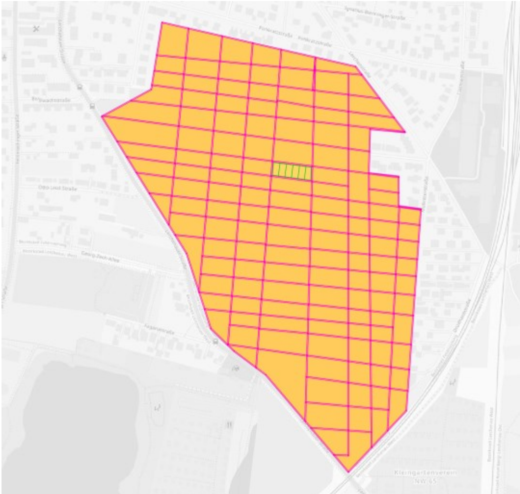


(2) Plot distribution

(3) Building allocation on plots

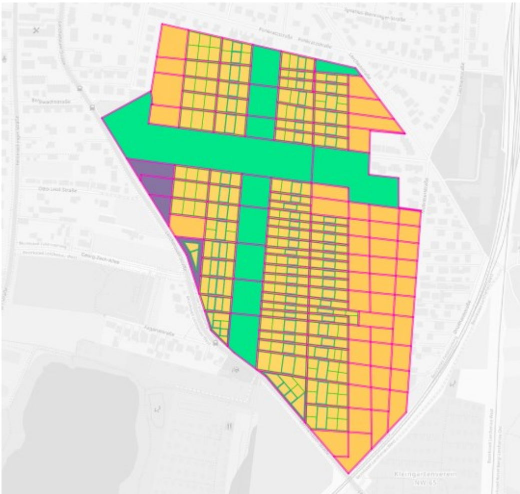
(4) Zoning

Figure F-2 Urban patterns of the final urban design outcome by participant F

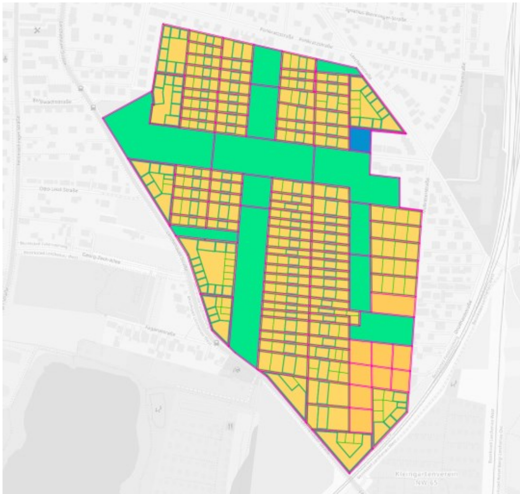


(1) Design session 1: Initial road network and block division

(2) Design session 2: Additional block transformation and initial plot generation



(3) Design session 3: Substantial block modification and defining zones



(4) Design session 4: The generation of the different buildings with various layout typology

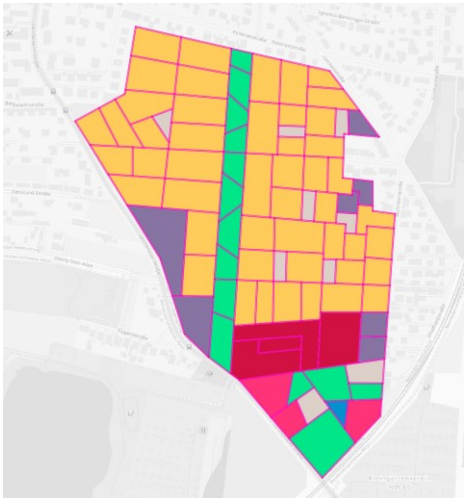
Figure F-3 Snapshots of design progress until reaching the final design outcome

As seen from a series of images of Figure F-3, participant F divides the intervention area into smaller areas by the grid pattern. Rather than making somewhat large blocks and dividing them into smaller plots, participant F tries to test a particular plot style with low-rise detached houses. After introducing this plot style, a network of greenery areas that connects individual plots is suggested by converting and merging small areas. Commercial areas are distributed to allow for easy access. The net duration of idea development is 118 minutes.

Participant G

Figure G-1 A screenshot of participant G's proposal for Lerchenauer Strasse

(1) A final urban design outcome

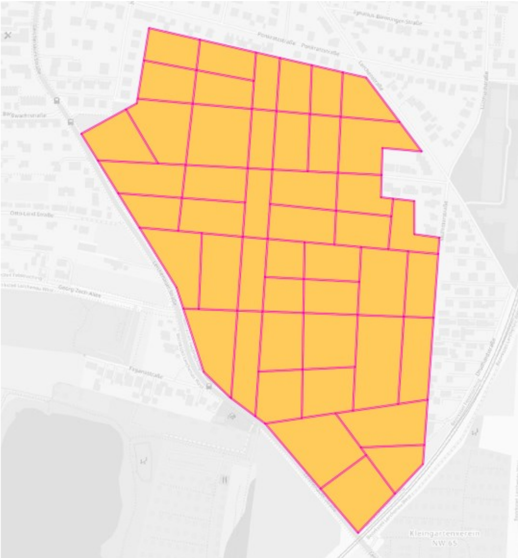


(2) Zoning

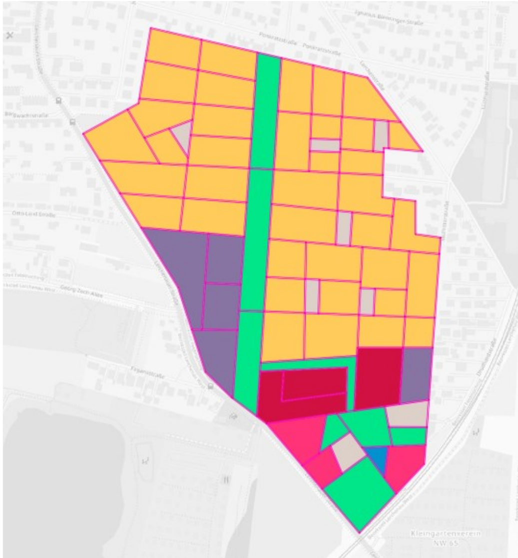
(3) Building allocation on plots

(4) Plot distribution

Figure G-2 Urban patterns of the final urban design outcome by participant G



(1) Design session 1: Initial road network and block division



(2) Design session 2: Additional block transformation and initial zoning

(3) Design session 3: Minor block modification and initial plot division

(4) Design session 4: The generation of the different buildings with various layout typology

Figure G-3 Snapshots of design progress until reaching the final design outcome

As seen from a series of images in Figure G-3, participant G tries to divide the intervention area into smaller blocks; however, functions of the blocks seem to be considered implicitly. After that, participant G specifies the function of blocks (i.e., commercial, green, education, sports, and water area). Participant G intends that the green area that divides east and west provides easy access to the lake. This forms a large public space, but rather smaller open areas are distributed between blocks. Once the basic town layout is defined, different block typologies are tested in consideration of density and the context of neighboring villages. For this exploration for finding more promising block configurations, the backtrackings in the design history management module are actively used to compare the changing design concepts.

Participant H

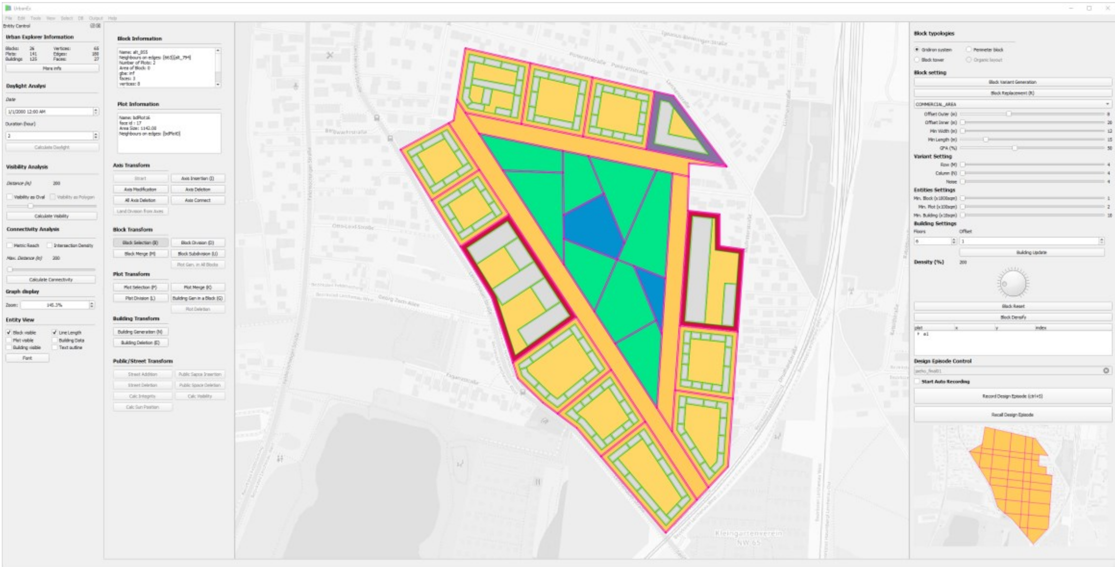
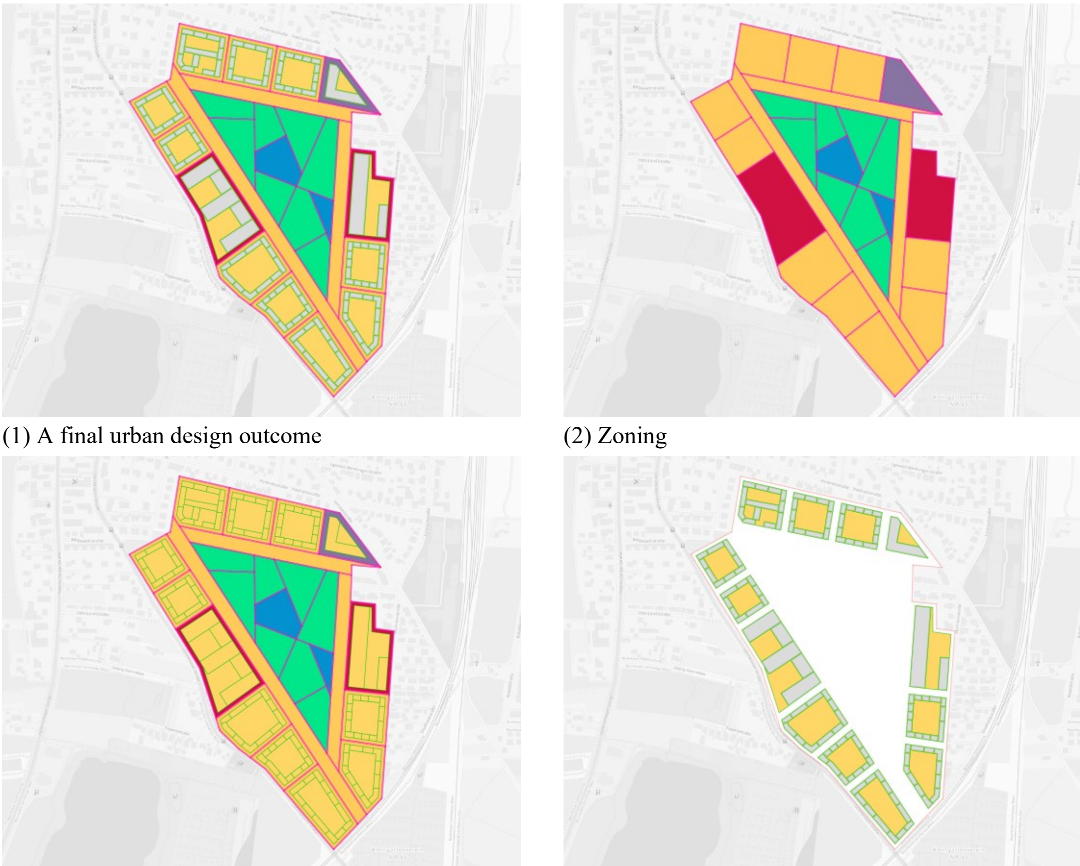


Figure H-1 A screenshot of participant H's proposal for Lerchenauer Strasse



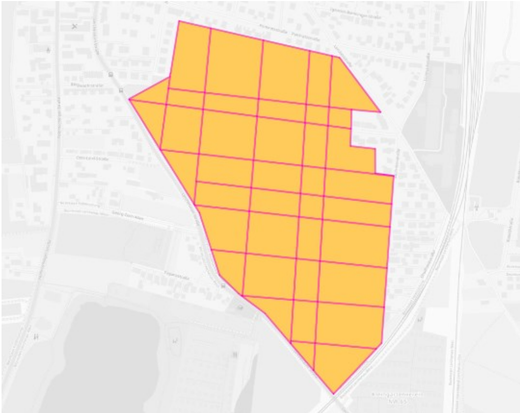
(1) A final urban design outcome

(2) Zoning

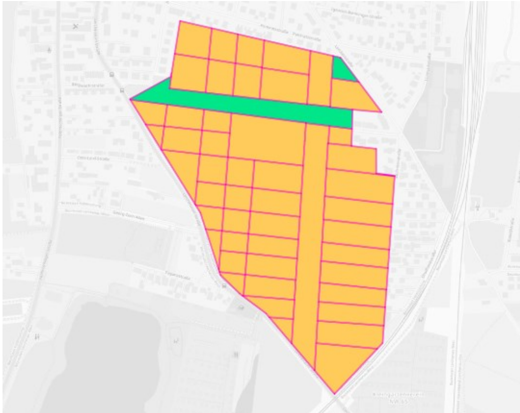
(3) Plot distribution

(4) Building allocation on plots

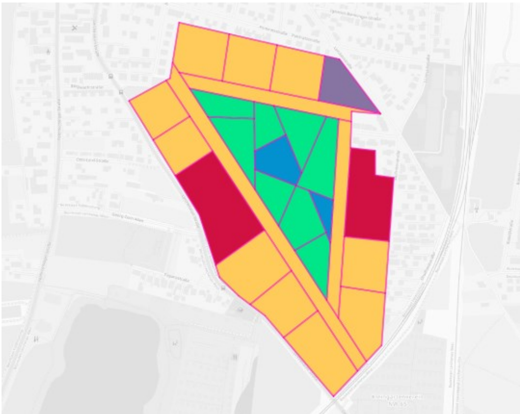
Figure H-2 Urban patterns of the final urban design outcome by participant H



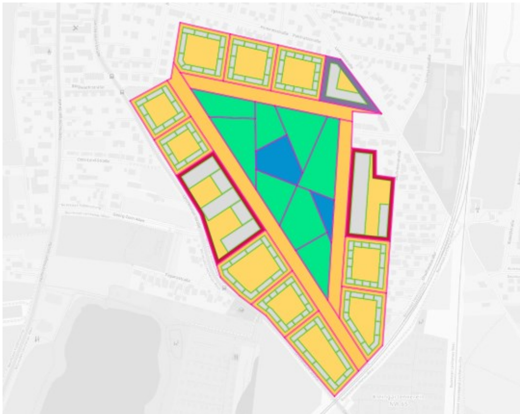
(1) Design session 1: Initial road network and block division



(2) Design session 2: Additional block transformation



(3) Design session 3: Developing new urban layout with initial zoning



(4) Design session 4: The generation of the different buildings with various layout typology

Figure H-3 Snapshots of design progress until reaching the final design outcome

Figure H-1 is the final urban design idea that participant H proposes, which features a large triangular open area in the center of the intervention site, surrounded by the dwelling, commercial, and education blocks. However, as can be seen in the first two images in Figure H-3, participant H initially developed the site layout with a regular grid pattern. At some point, while elaborating individual blocks, participant H finds the working urban concept less attractive, which leads to the development of a new urban configuration. By applying varied perimeter block housing typology, the site provides uniform open spaces. The net duration of design development is 109 minutes.

Participant I

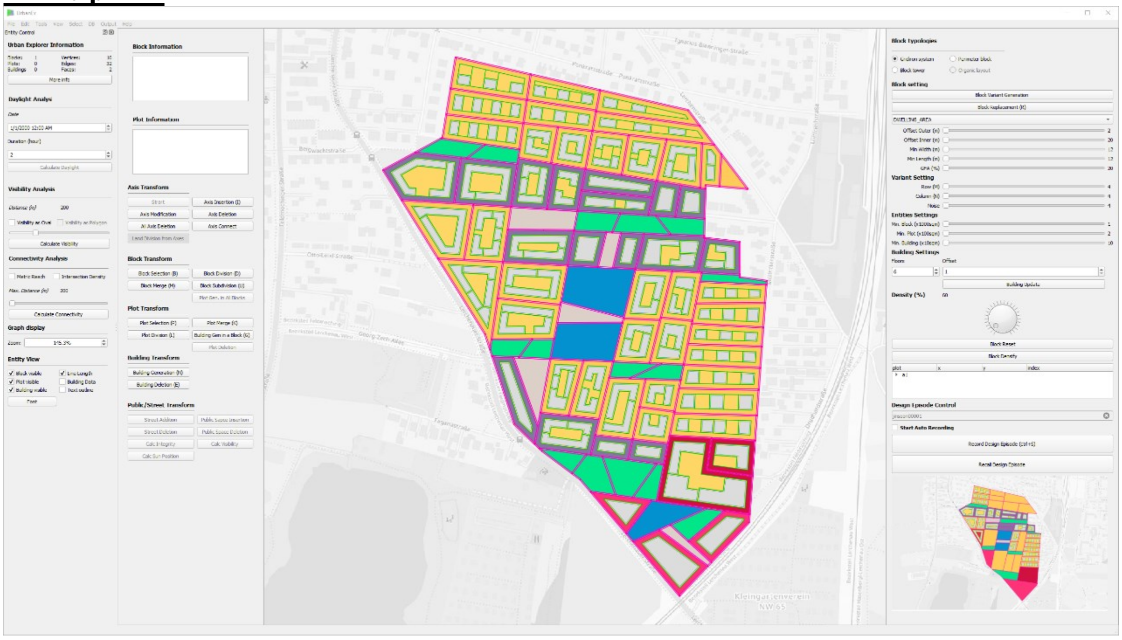
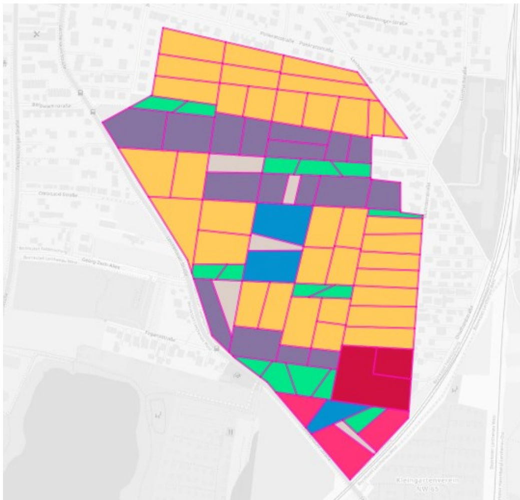
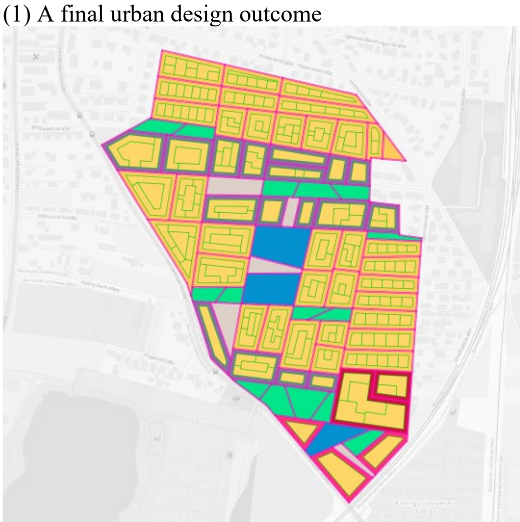


Figure I-1 A screenshot of participant I's proposal for Lerchenauer Strasse

(1) A final urban design outcome



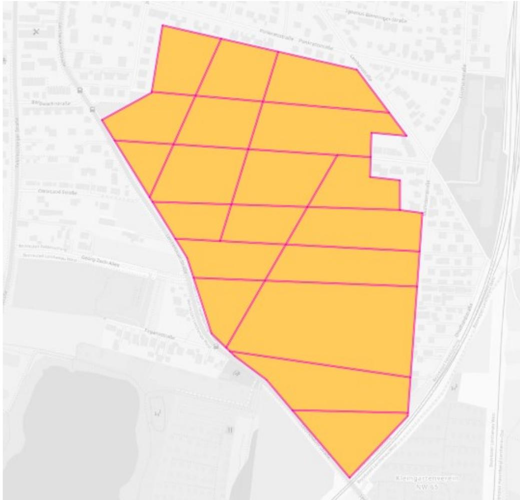
(2) Zoning



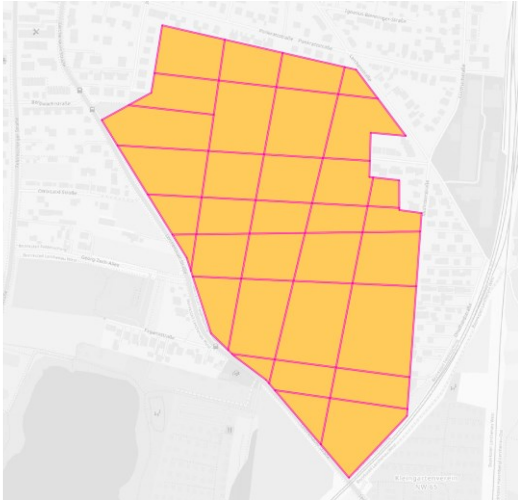
(3) Plot distribution

(4) Building allocation on plots

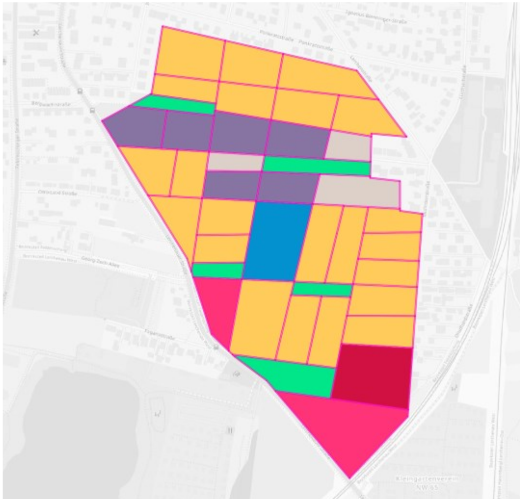
Figure I-2 Urban patterns of the final urban design outcome of the participant I



(1) Design session 1: Initial road network and block division



(2) Design session 2: Testing different urban layout



(3) Design session 3: Minor block modification and zoning

(4) Design session 4: The generation of the different buildings with various layout typology

Figure I-3 Snapshots of design progress until reaching the final design outcome

Before deciding the final layout concept, participant I tested varied urban configurations intensively by using multiple design history navigations. Figure I-1 shows the final urban design idea of the intervention site. From north to south, different functions of blocks are distributed (i.e., Figure I-2 (2)), and diverse building configurations are proposed. In the center of the site, the water area is placed, which is surrounded by medium-size perimeter block housings layer by layer. The blocks that are incident to the existing villages follow similar layout configurations with low-rise buildings. By considering living style, the commercial areas that also provide open space are placed near transportation spots. The net duration of idea development that participant I spent is 138 minutes.

Participant J

Figure J-1 A screenshot of participant J's proposal for Lerchenauer Strasse

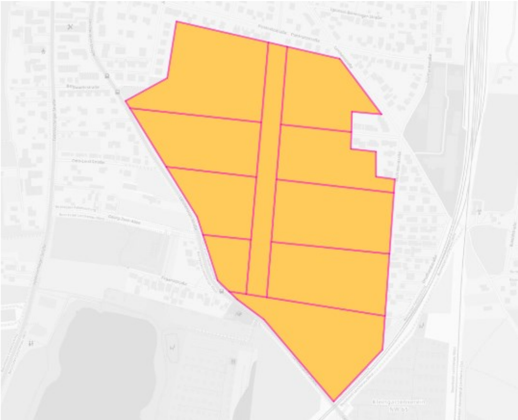
(1) A final urban design outcome

(2) Zoning

(3) Plot distribution

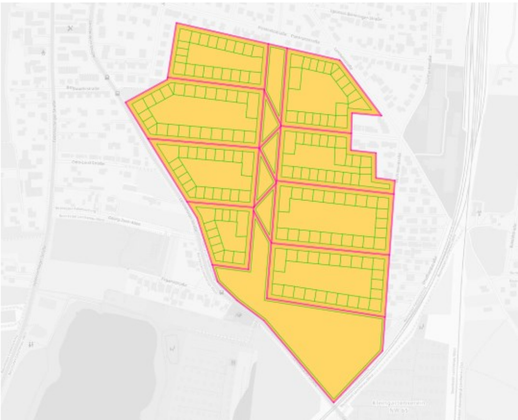
(4) Building allocation on plots

Figure J-2 Urban patterns of the final urban design outcome of the participant J



(1) Design session 1: Initial road network and block division

(2) Design session 2: Testing block layout



(3) Design session 3: Transforming block layouts

(4) Design session 4: The generation of the different buildings with various layout typology

Figure J-3 Snapshots of design progress until reaching the final design outcome

As can be identified through a series of images in Figure J-3, participant J comes up with the site's initial concept and sticks to this idea only with minor changes. Each block area, mainly perimeter block typology, is relatively larger than that of other test participants. Participant J divided the site into two, and the shallow area in the center becomes a waterside with greenery space. Participant J decided to use perimeter block housing initially; therefore, participant J tends not to use the automated generation of diverse block topology. The use of design history navigation was to recall the previous design idea only when a mistake in the current design stage was found. Rather than developing the urban design concept on a large scale, making variations manually at the block level is dominant.

The duration of design development is 1:33, and the use of a design variant generation was just once, but the suggested variant was not applied to the intervention area. He asked for more flexibility to define the function of the inner block area.

Participant K

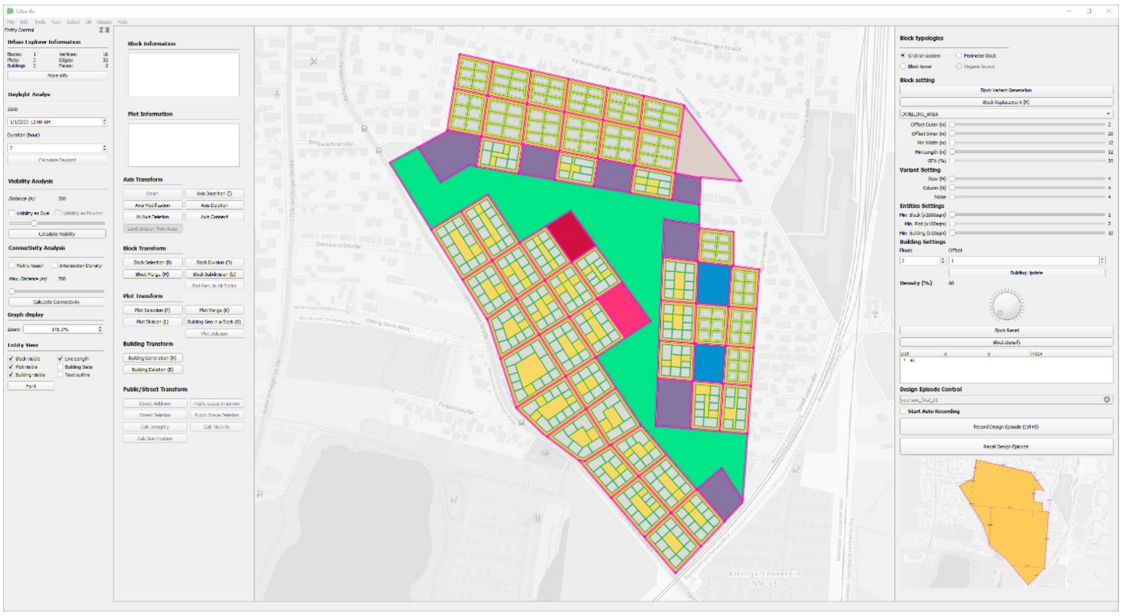
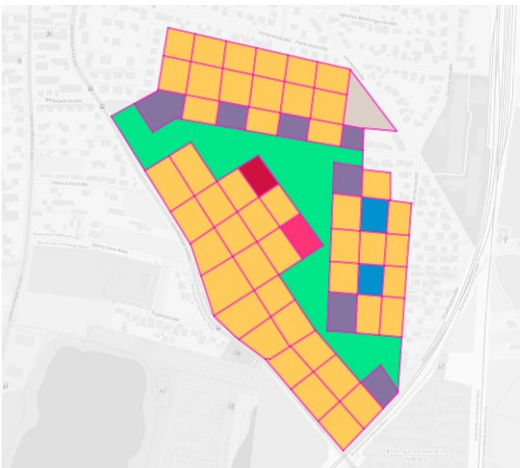


Figure K-1 A screenshot of participant K's proposal for Lerchenauer Strasse

(1) A final urban design outcome

(2) Plot distribution

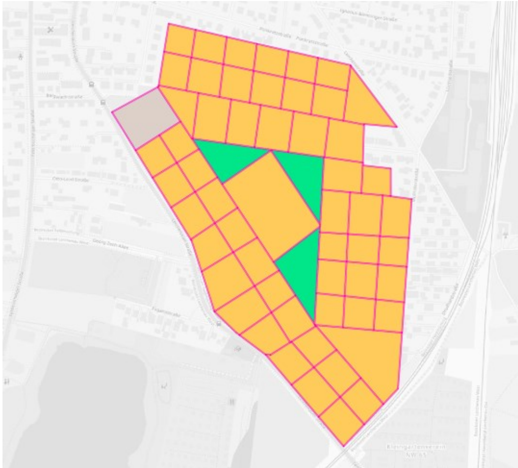


(3) Zoning

(4) Building allocation on plots

Figure K-2 Urban patterns of the final urban design outcome by participant K

(1) Design session 1: Initial road network and block division



(2) Design session 2: Testing different urban layout

(3) Design session 3: Minor block modification and zoning

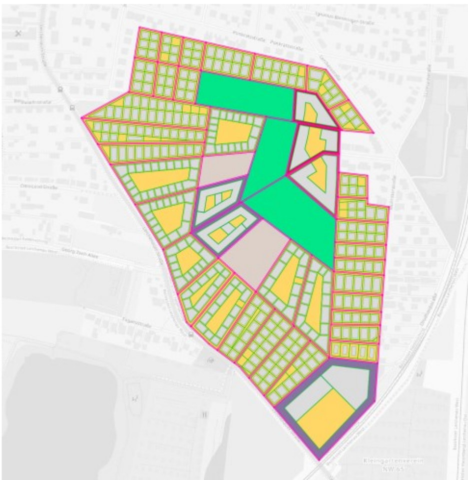
(4) Design session 4: The generation of the different buildings with various layout typology

Figure K-3 Snapshots of design progress until reaching the final design outcome

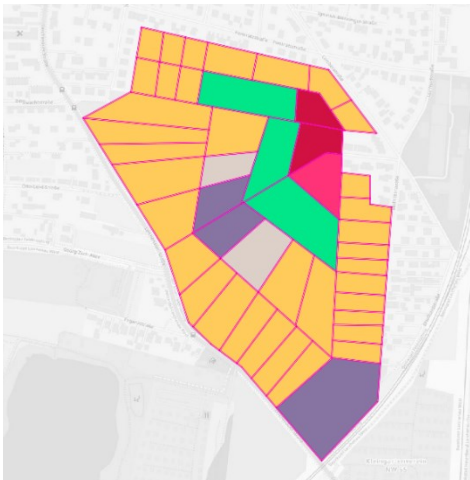
Figure K-2 shows the final urban design that participant K proposes after 121 minutes. Three distinctive areas in the north, in the east, and in the south-west surround the inner green area, which connects from north to south. Blocks in the north and in the east are gridiron layout typologies and remainings with perimeter block housing. Along the green area, the majority of commercial, education, and sports area is placed. Representative steps of idea development are shown in Figure K-3.

Participant L

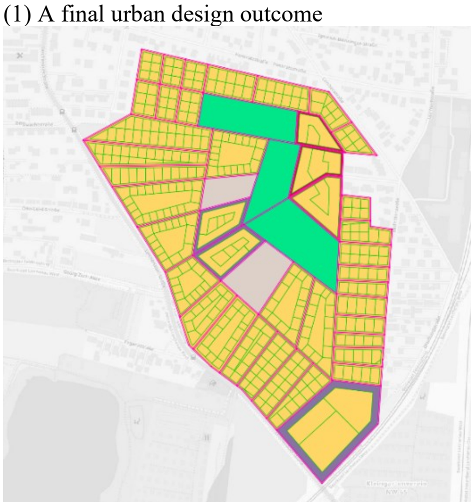
Figure L-1 A screenshot of participant L’s proposal for Lerchenauer Strasse



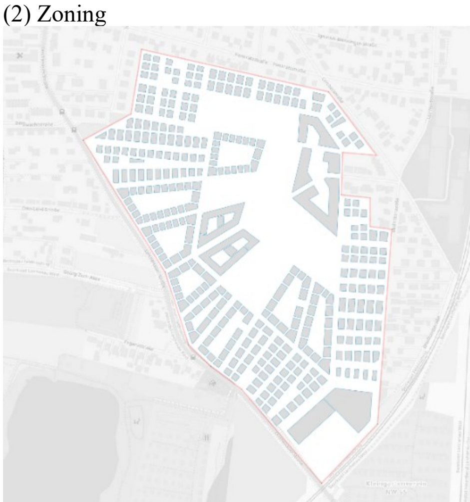
(1) A final urban design outcome



(2) Zoning

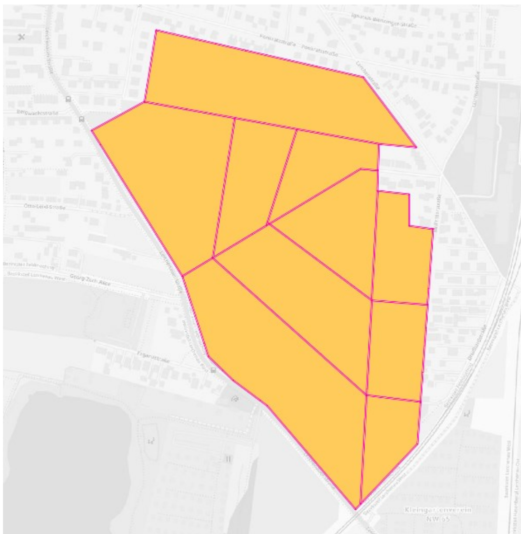


(3) Plot distribution

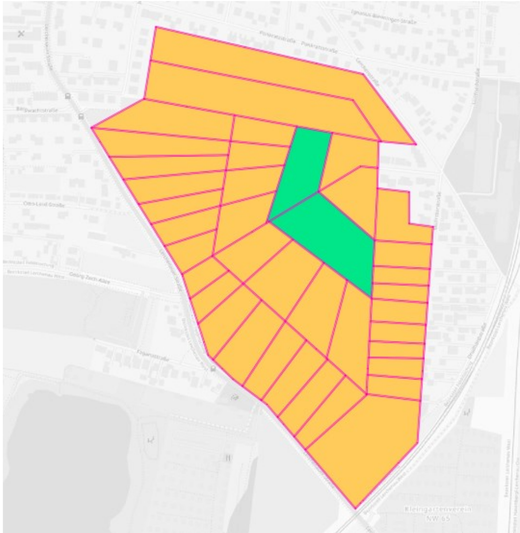


(4) Building allocation on plots

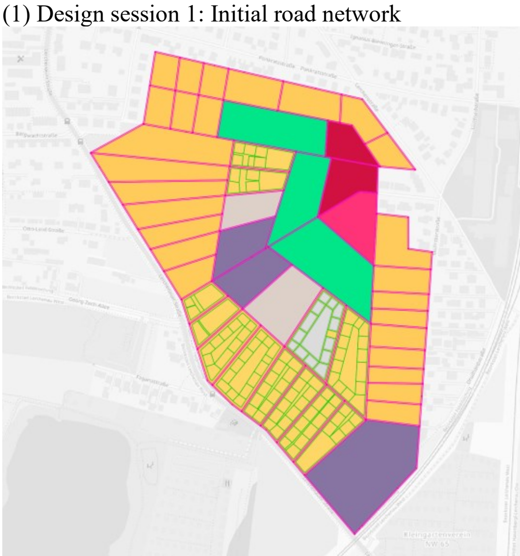
Figure L-2 Urban patterns of the final urban design outcome of the participant L



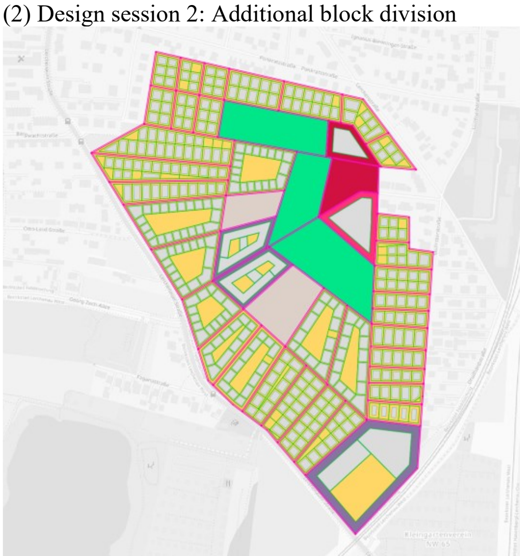
(1) Design session 1: Initial road network



(2) Design session 2: Additional block division



(3) Design session 3: Minor block modification and zoning/initial layout generation



(4) Design session 4: The generation of the different buildings with various layout typology

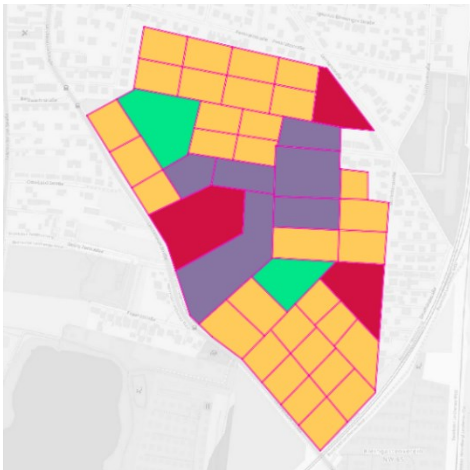
Figure L-3 Snapshots of design progress until reaching the final design outcome

Figure L-2 shows the final urban design outcome by Participant L. As can be identified in the first image of Figure L-3, participant L draws key axis lines after the site analysis and further divides the initial large blocks into smaller blocks. A large green area is placed in the center, which neighbors include commercial, education, and sports areas. Moreover, the large commercial area is planned in the southern area of the site by considering noise from the railroad. It seems that participant L decides to keep the initial idea and promptly increase the details of individual blocks generated automatically, without additional modifications. The net duration of idea development is 54 minutes.

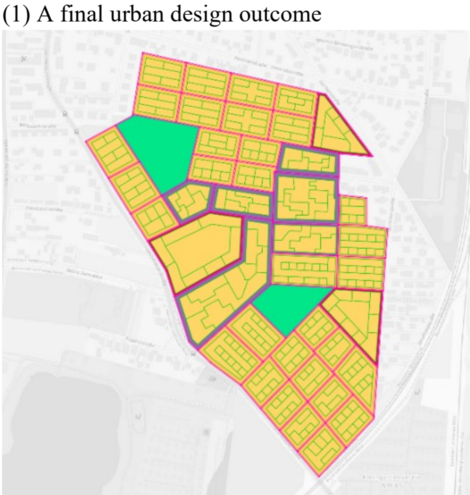
Participant M

Figure M-1 A screenshot of participant M’s proposal for Lerchenauer Strasse

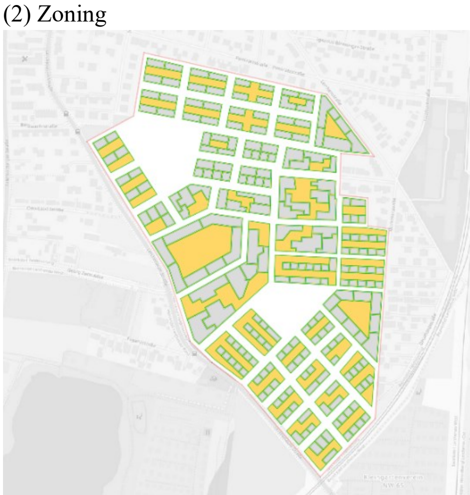
(1) A final urban design outcome



(2) Zoning

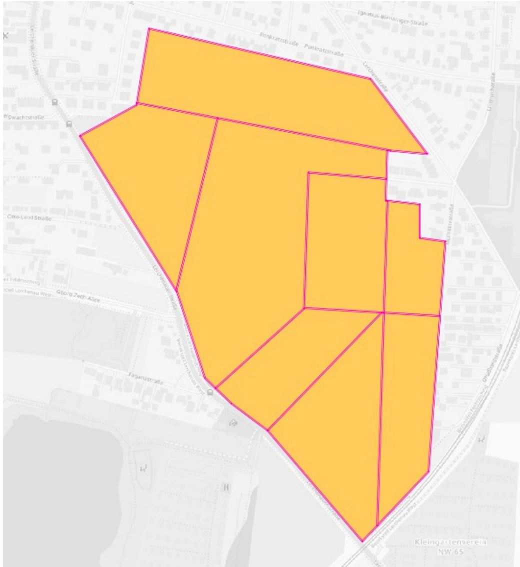


(3) Plot distribution

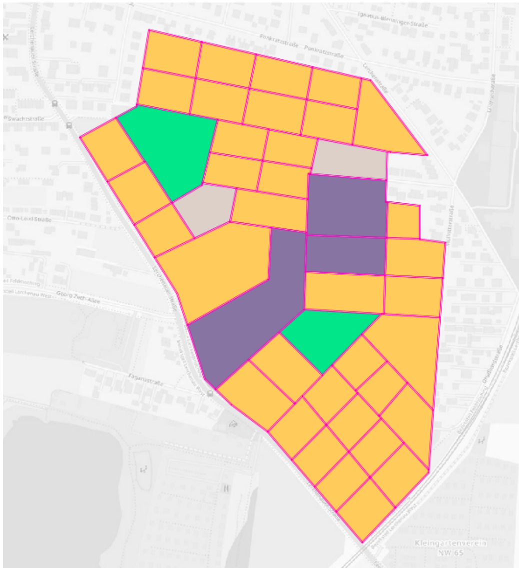


(4) Building allocation on plots

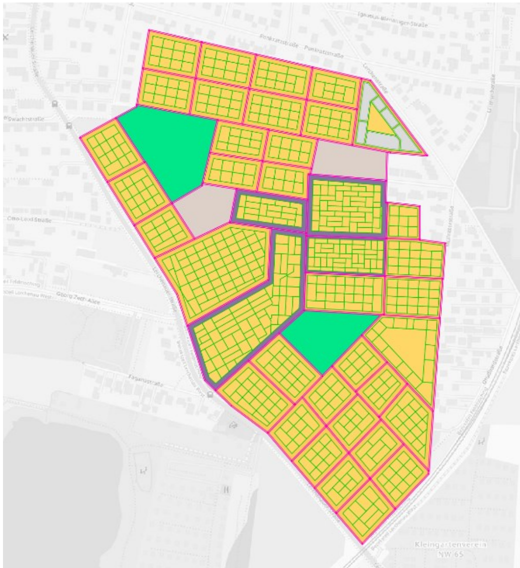
Figure M-2 Urban patterns of the final urban design outcome by participant M



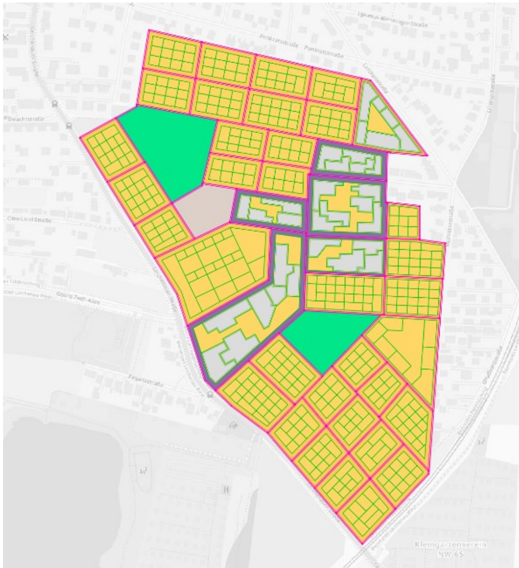
(1) Design session 1: Initial road network and block division



(2) Design session 2: Additional block division and initial zoning



(3) Design session 3: Initial plot division



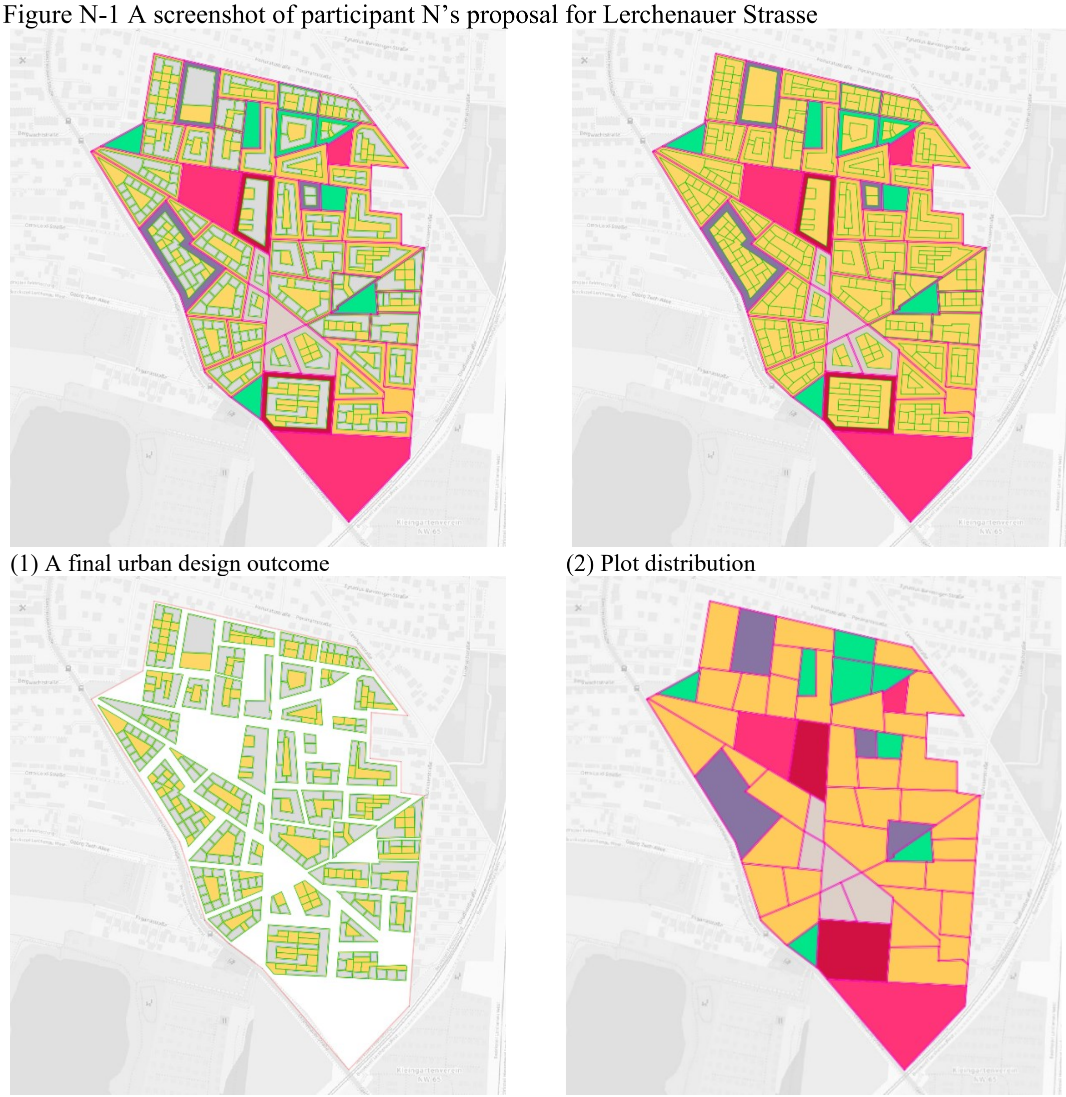
(4) Design session 4: The generation of the different buildings with various layout typology

Figure M-3 Snapshots of design progress until reaching the final design outcome

Figure M-2 shows the final urban design proposal by participant M. It has two green areas, between which several blocks for commercial functions are placed. As shown in Figure M-3, participant M draws an initial road network to create large blocks, which are further divided. Except for a few areas, participant M decided to use gridiron block patterns. In the case of dwelling areas, uniform building patterns are preferred, but in the case of commercial areas, relatively freeform building configurations are adapted for aesthetic reasons. Backtracking is used only once, and the net duration of idea development is 73 minutes.

Participant N

Figure N-1 A screenshot of participant N's proposal for Lerchenauer Strasse



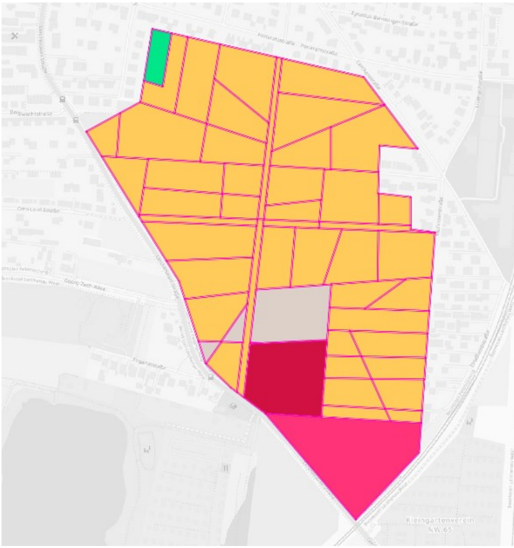
(1) A final urban design outcome

(2) Plot distribution

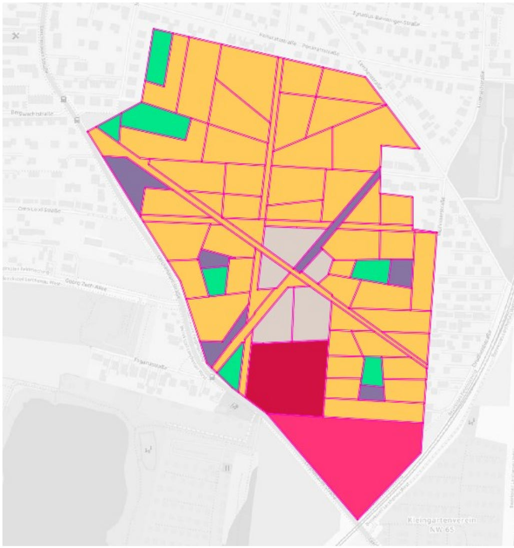
(3) Building allocation on plots

(4) Zoning

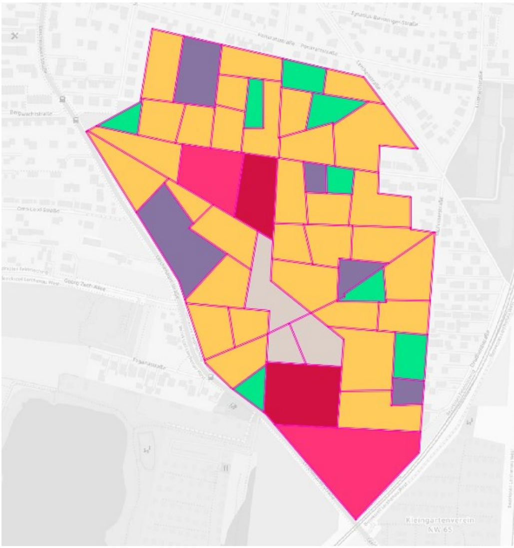
Figure N-2 Urban patterns of the final urban design outcome of the participant N



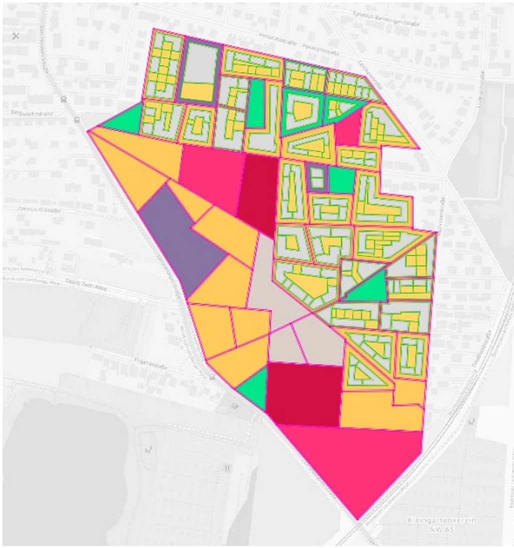
(1) Design session 1: Initial road network and block division are tested



(2) Design session 2: Additional block division and initial zoning



(3) Design session 3: Minor block modification and resizing



(4) Design session 4: The generation of the different buildings with various layout typology

Figure N-3 Snapshots of design progress until reaching the final design outcome

Participant N initially tries to identify the site context, such as neighboring building types and road networks, before defining axes. Since then, Participant N continuously increases the site's complexity by adding axes and matching schematic functions with the subdivided areas. When dividing blocks into smaller blocks, instead of applying perpendicular axes, Participant N introduces slightly diagonal lines, and repeatedly, Participant N analyzes the context of the site when this person finds uncertainty of the current working idea. When the block division reaches a certain level of manageable size, two superimposing axes are inserted onto the existing block configuration in order to increase connectivity with incident areas. Particularly, the one is to make an effective connection between the neighboring train station and the lake, and the other is to make a shorter travel distance by considering the shape of the intervention site. However, Participant N identifies that these two superimposing axes do not get along with the existing axes, so she develops another idea in which the diagonal axes are drawn first, and the grid patterns are followed. Participant N uses the alternative generation function quite actively, but the generated block typologies are frequently further transformed to make rather diverse block layouts.

The main courtyard is placed in the center of the site and the sports area in the south. Green space and shops are placed somewhat evenly. In the center, the average building has six floors and 56 blocks. The duration of idea generation is about 1 hour 58 minutes.

- The End of Appendix -