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Doctoral Dissertation

An Interaction-Based Design Approach for Architecture as A Complex Adaptive System

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Abstract

Creativity is a vital issue in design studies, a great number of literatures approach to design creativity from the perspectives of cognitive and social. Additionally, many creative methods and tools for design thinking are considered and built. These methods and tools for enhancing design creativity are related with two kinds of aspects, one is the process of design and the other is the outcome of design. However, their methods for creative architecture design were mainly belong to reductionist thinking, the complex nature of architecture in the 21st century is ignored.

In this dissertation, we first review the simplicity and complexity of architecture. On this background, we acknowledge architecture as a complex adaptive system (CAS) and present a new design thinking approach 'Concept Topology Optimization' (CTO) for creative architecture design. Then we conducted three case studies by utilizing 'Concept Topology Optimization' to explore new methods in architecture location design, architecture space design and architecture construction safety design.

As case studies, three proactive methods are presented. The first case discusses a Soil & Water Assessment Tool （SWAT） model-based expo architectural location design, the second case explores a new method for architecture space design based on Substance-field and the third case focus on design of building construction safety prediction model based on optimized BP neural network algorithm. The results of these case studies indicate that 'Concept Topology Optimization' is an effective design thinking approach in architecture design as a complex adaptive system. After that, we further discuss the changes of knowledge creation by combining 'Concept Topology Optimization', 'creativity' concerns the process of creating and applying new 'knowledge', intrinsically, 'creativity' is at the very heart of 'knowledge creation'. However, our 'creativity' is 'blocked' in a variety of ways, including deep-seated beliefs about the acquired knowledge. Hence, we argue to accept unpredictability, respect (and utilize) autonomy and creativity, and respond flexibly to emerging knowledge and opportunities.

Keywords**:** Creativity, architecture design, complexity science, topology, SWAT model, TRIZ theory, BP neural network algorithm

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Chapter 1 Introduction

1.1 Research Background

1.1.1 Problem Definition of Architecture Design

The need of proactive methods for creative conception and strategies have been emphasized by numerous researchers (Jones, 1992). Meanwhile the design process of contemporary architecture become more complex because of influential factors such as increasing the size of designed projects and the size of stakeholders (Kiatake & Petreche, 2012).

Design activities can be assumed as problem solving by a broad definition of problem and problem solving (Moursund, 2004). Lawson (2012) stated that in the most general sense we can view problem solving as a very basic human activity and designing can be seen as a kind of problem solving. Meanwhile, the problems can be classified into well-defined (well-structured) and ill-defined (wicked) problems (Schacter, Gilbert & Wegner, 2009； Cross, 2000). Well-defined problems are those who have a clearly defined goal, mostly one correct answer and a clearly defined path to solve, such as playing chess, mathematic problems (Cross, 2000) while ill-defined problems do not have clearly defined goals or clear path to solve the problem. Rittel & Webber (1973) contended the idea of ill-defined problems. They argued that the problems that socialists or designers are dealing with totally are different from scientists' or engineers' problems and design problems are ill-defined problems. Based on it, architecture design is ill-defined (wicked) problem.

1.1.2 Changes in Theoretical Methodology

When the world is technically moving towards integration, the knowledge world is more and more divided. The root cause of this phenomenon is that since the scientific development has evolved from the ancient visual speculation (Renfrew, Ezra and Francoise, 1994) to the modern experience analysis (Simmons,1963), the traditional academic research route is based on the hypothesis of reductionism (Putnam,1973). Based on it, every phenomenon in real world can be regarded as a collection or composition of lower-level, more basic phenomena, so that the law of low-level motion forms can replace the law of advanced motion forms. Therefore, by continually subdividing research, researchers finally gained the understanding of the advanced laws. As a result, the disciplines are becoming more and more detailed and the number of specialized knowledge outputs is becoming more and more huge; the gaps among various disciplines are growing so that people can't be able to make a clear overview. The separation weakens the communication among various disciplines. For example, in terms of human, biology, psychology, medicine, and sociology all define human as different objects of knowledge. Although these knowledges point to the same submit, the concepts of each other are almost incommensurable. In 1929, Martin Heidegger (Heidegger, 1929) wrote an article criticizing that 'The field of science is now fragmented and the research methods of various disciplines are fundamentally different'. Nowadays, this hodgepodge of various disciplines is maintained only by the specialized organizations in universities and faculties to ensure its completeness. It can only retain its significance through the actual purpose of different branches.

The reductionism is already exhausted, and the way out is Nobel Prize winner Herbert Simon (1991) pointed out that since the First World War, there has been a holistic theory 'Complexity Theory' in the West which is different from the ancient ones. Since the mid-20th century, people have shown intense interest in complexity and complex systems. After the First World War, an early wave of interest led to the birth of the word 'Holism' (Smuts,1926), which led to a keen interest in 'Gestalt' (Perls & Andreas, 1969) and 'Creative Evolution' (Bergson, 1984). In the second round of interest waves after the Second World War, the hot words were 'Information', 'Feedback', 'Cybernetics' and 'General System'. In the current wave, the words often associated with complexity are 'Chaos', 'Adaptive Systems', 'Genetic Algorithms' and 'Cellular Automata'. Although reductionism still plays an important role, the theoretical paradigm has quietly changed from reductionism to complexity.

1.1.3 Developing Trend of Architecture Design

The way of global development is changing from the pattern of 'industry-expansion' to the sustainable pattern of 'information-ecological' (Yan & Dong, 2003) and simplicity paradigm is being replaced by complexity paradigm. A new type of society-information society is taking shape in the global integration of the digital platform. The traditional drawing board has been replaced by computer screen, most of architecture professional basis has been changed by emerging technologies, such as the information and internet based working methods and complex ecological issues. Among these technologies, building information modeling (BIM) is one of the most hopeful recent developments in the architecture, engineering, and construction (AEC) industry. With BIM technology, an accurate virtual model of a building is digitally constructed (Azhar, 2011). Figure 1.1 shows an example of BIM.

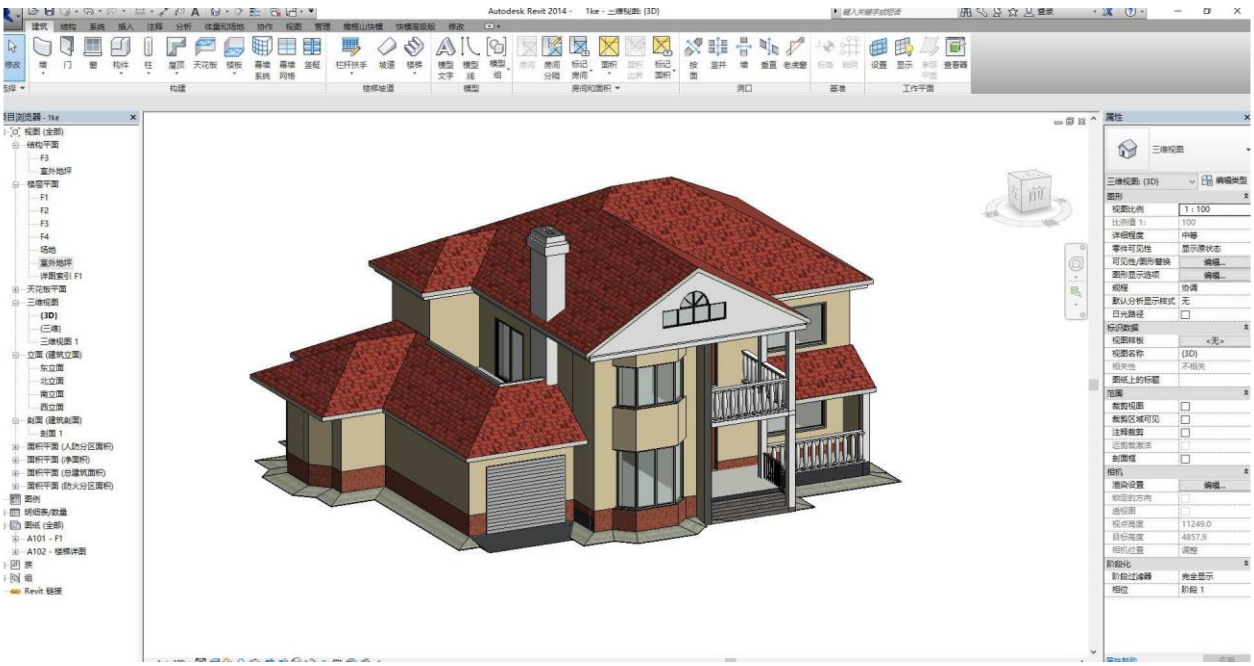

Figure 1.1 An example of BIM

BIM presents a new model within AEC, one that encourages integration of all people on a project by building the relationships among architecture, management, control, fabrication, detailing and engineering (Sacks et al.,2010). These parts interact and finally form a changing architecture system interacting with its environment (Gann,2000). Figure 1.2 shows the role of BIM in architecture.

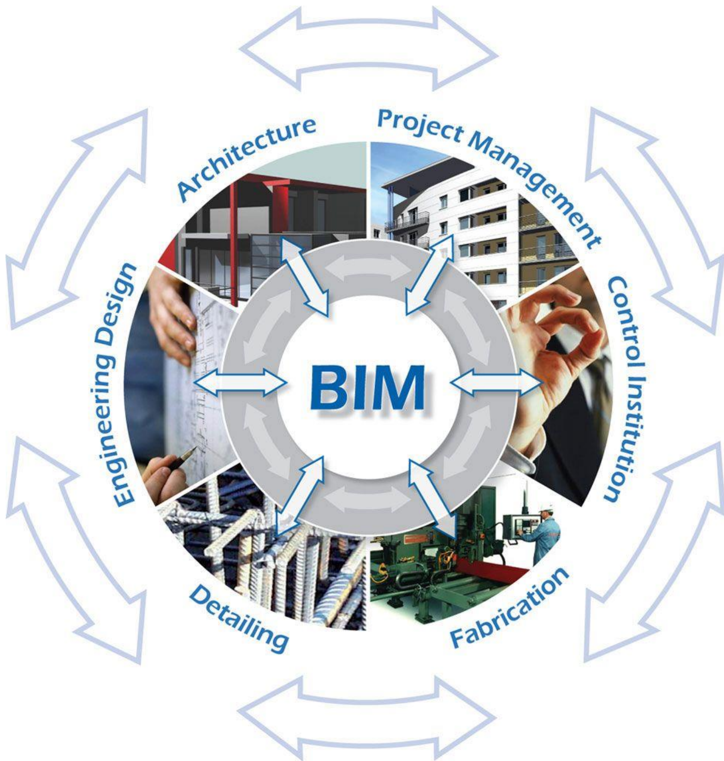

Figure 1.2 The role of BIM in architecture.

(Figure Source: http://t.zhulong.com/u10846278/weibo)

1.1.4 Simplicity

Newton (Newton, 2008) describes the four principles of scientific methodology in The Mathematical Principles of Natural Philosophy. The first one gives a precise overview of the principle of simplicity: 'Besides those who are real enough to explain their phenomena, there is no need to seek other things in nature'. Newton explained that 'nature is not useless, and if it is less self-contained, it is useless to do more, because nature likes simplicity and does not like to boast of itself with superfluous reasons.' This principle became the common principle followed by researchers. Seeing simplicity as an intrinsic property of nature, including Einstein, who does not deny the principle that 'the most basic concept of science, by its nature, is simplicity.' Scientific understanding has long been and is still often thought of as the mission of dispelling the complexity in order to reveal the simple order they follow.

1.1.5 Complexity

As complex science is still in its infancy, the existing definitions of complexity vary widely and cannot be unified. However, although there is no authoritative definition, the direction of complexity research is still clear. The identifiable complexity includes not only the number of system elements and the number of interactions, but also the uncertainty, indeterminacy, and complexity of random phenomena. In a sense, it always deals with contingency and this contingency cannot be recognized or eliminated by our simplified reduction measures.

1.1.6 Complex Adaptive System (CAS)

A complex adaptive system is a system where a perfect understanding of the individual parts does not automatically convey a perfect understanding of the whole system's behavior (Miller & Page, 2009). The study of complex adaptive systems, a subset of nonlinear dynamical systems (Lansing, 2003) is highly interdisciplinary and blends insights from the natural and social sciences to develop system-level models and insights that allow for heterogeneous agents, phase transition, and emergent behavior.

1.1.7 Definition of Interaction

Nicolas (2017) gave the definition of ‘interaction’ in his book ‘Understanding Interactions in Complex Systems’ which means the mutual action or influence which may exist between two or more objects, two or more organs, and even to or more phenomena’, and it is always followed by one or several effects.

1.2 Research Questions

Previous sections has introduced the background of changes in architecture design and theoretical methodology , thus we propose the following research questions：

MRQ: What are the effective design approaches for architecture as a complex adaptive system?

SRQ 1: What are the characteristics by acknowledging architecture as a complex adaptive system (CAS)?

SRQ 2: How can designers utilize the characteristics by acknowledging architecture as a complex adaptive system (CAS) to develop new design approaches for architecture?

SRQ 3: What can examine the effectiveness of the new design approaches?

1.3 Research Purpose

This thesis aims to acknowledge architecture as a complex adaptive system (CAS). On this basis, we further aim to propose a new design thinking approach ‘Concept Topology Optimization’ for effective architecture design at a large and complex scale.

1.4 Research Methods

In this thesis, we adapt mixed research methods to achieve complementary advantages. Three main aspects are outlined below and Figure 1.3 shows specific research methods in each chapter.

1.4.1 Interdisciplinary Research Methods

Interdisciplinary research is a form of support and integration-oriented cooperation between researchers from different disciplines (Pohl & Hadorn, 2007). In this thesis, we combine mathematical definitions of topology and topology in practice, not just limited to architectural design theory in the field of architecture.

1.4.2 Quantitative & Qualitative Research Methods

In this thesis, we combine quantitative and qualitative analysis methods. Chapter 1-3 utilize the qualitative research methods including comparative analysis, inductive analysis, deductive analysis and literature review. Chapter 4-6 utilize the quantitative research methods including empirical research, controlled experiment analysis and simulation experiment analysis.

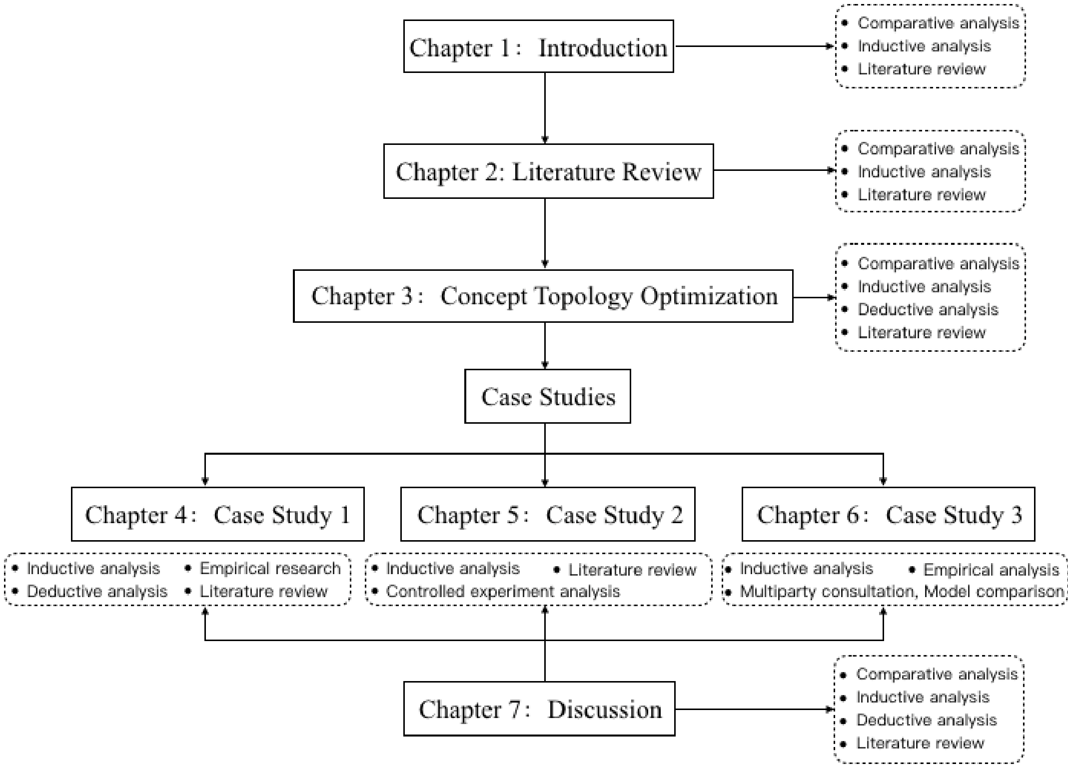

Figure 1.3 Specific research methods in each chapter

1.5 Research Contributions

In this thesis, the science of complex adaptive systems provides important concepts and tools for responding to the challenges of architecture design in the 21st century. New thinking approach that incorporate a dynamic, emergent, creative, and intuitive view of architecture design must replace traditional "reduce and resolve" approaches to architects.

School of Knowledge Science in JAIST fuses learning fields at the cutting edge of 'knowledge creation' in the humanities, social sciences, and natural sciences with the aim of discovering mechanisms that create, accumulate, and utilize knowledge and generating ideas on the design of our future society. This philosophy gives people great freedom to achieve 'knowledge creation' without confinement to existing academic disciplines. To sublimate such a crucial subject in KS, this thesis contributes to the creative integration of various disciplines under the context of complexity and shows how a CAS framework can guide future research and theory.

1.6 Structure of this Thesis

This thesis consists of 8 chapters as shown below.

Chapter 1 Introduction

This chapter first introduces the research background in this thesis, including the problem definition of architecture design, developing trend of architecture design and changes of theoretical methodology. After that, three basic concepts in this thesis are explained. Finally, we present our research questions, research purpose and research contributions in this chapter.

Chapter 2 Literature Review

This chapter first reviews the simplicity and complexity of architecture and point out the necessity of complexity in architecture. Then we review the complexity theory and summarize the useful consensus on the complexity. After that, we construe architecture as a complex adaptive system (CAS) as it satisfies the seven basic characteristics of CAS. Accordingly, we summarize the advantages of viewing architecture as a CAS in the end of this chapter.

Chapter 3 New Design Thinking Approach: 'Concept Topology Optimization'(CTO)

This chapter first reviews the content of topology and explains the reason why topology can attract our attention for proposing the new design thinking approach. Then we present the definition and basic model of 'Concept Topology Optimization'. Reasons of conducting the three case studies and relationships among the three case studies are also explained in this chapter.

Chapter 4 Case Study 1: SWAT Model-Based Ecological Expo Architecture Location Design

We believe that rather than being regulated by technology, architects should exploit it so as to promote the basic needs of ecology. In this chapter, we first introduce the concept 'Ecological Architecture', then we propose five design principles for ecological architecture design. Further, we use the first level of CTO to aid in the expo-architecture location design and make architecture more environmental to local ecosystems in LinGang wetland park. In this case study, building is the design agent, local ecosystems is the environment and SWAT model is the ground structure.

Chapter 5 Case Study 2: A New Method for Human-Centered Architecture Space Design Based on Substance-Field Analysis

Substance-Field (Su-field) Analysis is a TRIZ analytical tool for modeling problems related to existing technological systems. Meanwhile, the space concept is vital in architecture. This chapter aims to use the second level of CTO to developing a new method for more creative human-centered architecture space design. In this case study, human is the design agent, 'field' for human is the environment and Su-field analysis model is the ground structure. A controlled experiment demonstrates the effectiveness of this method by measuring idea quality and quantity.

Chapter 6 Case Study 3: Design of Building Construction Safety Prediction Model Based on Optimized BP Neural Network Algorithm

This chapter aims to use the third level of CTO to solve building workers' safety problems in building construction. In this case study, worker is the design agent, construction environment is the environment and BP Neural Network Algorithm is the ground structure. Firstly, the characteristics of the construction industry were analyzed. As a labor-intensive industry, the construction industry is characterized by numerous factors such as large investment, long construction period and complicated construction environment. Due to the increasingly serious security problem, widespread concern over such problem has been aroused in society. As a result, we argue the optimal 'safety' in building construction is the emergence of 'safety prediction'. Secondly, the problem of building construction safety management was summarized, six influencing factors were explored and a building construction safety prediction model based on rough set-genetic-BP neural network was established. Finally, the model was validated by a combination of multiparty consultation, empirical analysis and model comparison. The results showed that the model accurately predicted the risk factors during the construction process and effectively reduced casualties. Therefore, the model is feasible, effective and accurate.

Chapter 7 Discussion

This chapter consists of two parts, the first part discusses the applications and implications of CTO in the three case studies (from Chapter 4 to Chapter 6). The second part discusses CTO' s contributions to Knowledge Science, in which the relations between 'creative intelligence' with ‘knowledge intelligence’ and the contradiction between them are pointed out, how to solve the contradiction seems a tough problem in knowledge science. But fortunately, this contradiction is not unsolvable, CTO might be a good solution as it contributes to facilitating ‘effective creativity’ in process of knowledge creation.

Chapter 8 Conclusion and Future Work

The last chapter answer the SRQs and MRQ presented in Chapter 1and provides a summary of the whole thesis including findings and outcomes, as well as the research work in the future.

Chapter 2 Literature Review

2.1 The Simplicity and Complexity of Architecture

Modernist architecture pursues simplicity, both in faith and in specific practical strategies. The characteristics of the world that modernists dream of are one-objectivity, regularity, predictiveness, and control (Frampton & Futagawa, 1983). But this view of the world (a presupposition of the world view) is unrealistic in the contemporary sense and has a utopian color. In the process of continually simplifying, it is easy to lose the quality that should be possessed in the whole. With the aging of the first generation of modernist architects, later architects have increasingly found that modernist architecture is highly selective in deciding what problems to solve, thus it ignores many aspects of architecture (Klotz & Donnell, 1988). If the modern architecture tries to figure out more complex problems, it will become weak (Frampton, 2015).

That is to say, the problem recognition of modern architecture is also the premise and hypothesis of defining the problem—the complex world is compounded by simple things. But after the epoch-making ‘Complexity and Contradiction in Architecture’ of Robert Venturi (1977), the architectural trend can no longer return to pure modernism.

Today, most front-line architects are discussing the indefinite complexity and different expressions, but they all admit that such a world is complex and buildings cannot be avoided. Various pioneering building communities are hot on the scientific terminology of complexity, such as emergence, nonlinearity, and so on. A variety of complex patterns such as drops, vesicles, and fragments appear in various architectural magazines to capture people's attention.

What is complexity? What are the characteristics of complexity? How do architects examine and express the complexity of architecture? These will be the focus of this section.

2.2 Complexity Theory

In usual rhetoric, complexity is opposite to simplicity. But in the discussion of complexity research, the opposite of complexity is that each part is independent of each other and ‘complicated’ is opposite to simplicity. The concept of complexity not only represents the huge number of components in a system but also represents the huge number of interactions in the system.

Unfortunately, as the concept of complexity in scientific research, there is no unified conclusion. According to Lloyd's statistics (Horgan, 2015), there are 45 definitions of complexity and in fact it does not stop there.

Although there is no uniform definition of complexity, there is still some useful consensus on the complexity as shown in Table 2.1. The complexity paradigm is marked by re-establishing the fundamental attribute status of complex things, it is believed that complexity is ubiquitous. Any complexity phenomenon is not just a superposition of simple phenomena. Complex phenomena have the properties that are not available in simple components, so simplicity is only the starting point rather than the end point of the problem of complexity. Complexity believes that the reason why people pay more attention to simplicity in the past is not that it is the essence of things, but limited by then research methods so that they cannot understand and explain the results of complex phenomena (Standish, 2008).

Table 2.1 Understanding & definition of Complexity by key scholars

Key Scholars &Research Groups	**Main Concepts**	**Understanding & Definition of Complexity**
Edgar Morin (1967)	Complexity Approach	The first person to present a systematic approach to complexity. His complexity method mainly uses the conceptual model of 'Diversified Unification' to correct the cognitive method of reductionism in classical science, he also criticizes mechanical determinism with the concept that the basic nature of the world is unity and disorder. He proposed that the background of the object should also be part of the research and should not be stripped in order to oppose the pursuit of perfect understanding in the

		closed system to correct the simple overall principle of the traditional system view.
Ilya Prigogine (1975)	Dissipative Structure Theory	He demonstrated the concept of complexity science and the resounding slogan of ‘exploring complexity’. The study of distance-freeness was carried out and the theory of dissipative structure was proposed by him to provide a common theoretical weapon for complexity research around the world.
Haken Hermann (1980)	Synergetics	Synergetics is an emerging comprehensive academic interest that studies the evolutionary law of collaborative systems from disorder to order. Synergetics applies to the formation of ordered structures or functions that occur in non-equilibrium states, as well as to phase transitions that occur in equilibrium states.
The Santa Fe Institute (1992)	Complex Adaptive System (CAS)	The main characteristics of the complex adaptive system theory are: 1. Agent is an active, living entity which capable of adapting to the environment. 2. The interaction between individuals and environment is the driving force for the evolution of the system. 3. Link macro with micro organically. 4. Introduction of random factors makes it has a stronger description and expression ability.

Complexity is a theoretical paradigm that permeates research in specific disciplines, scholars from all over the world have different research perspectives about it. In order to discuss complexity, many scholars consider it's not necessary to define the concept of complexity, but we can establish a description of the complexity of features, which is helpful for us to understand the complexity and find consensus. Table 2.2 shows the characterizations of complexity we generalize from the literature review (Byrne, 2005).

Table 2.2 Characterizations of complexity

Characteristic	Description
Dimension	A complex system must have a certain degree of dimension with a large number of basic unit elements and components. This is the necessary condition for the complexity of the system.
Plentiful Interactions	To form a complex system, there must be interactions between the basic units, these interactions must be dynamic. Interactions can be not only physical but also informational.
Nonlinearity	The inputs and outputs of complex systems do not conform to the properties of the superposition principle. Nonlinearity guarantees properties that small causes can lead to large results.
Recurrency	Any effect of the effect can be fed back to itself. Such feedback can be positive feedback or negative feedback. Both feedbacks are necessary for complex systems
Partial Response	Each basic unit is ignorant of the overall behavior of the system, and it only responds to the available local information. That is to say, there is no system center of omnipotence. Complexity is the result of plentiful interactions between elements that respond only to the limited information available.
Openness	Complex systems are usually open and interact with the environment. In fact, defining the boundaries of complex systems is often difficult. The extent of the system is not a feature of the system itself, it is

	determined by the description of the system and is influenced by the position where the observer is. This process is called 'framing'.
Non- Equilibrium	Complex systems operate away from equilibrium. Therefore, there must be continuous energy to maintain the organization of the system and ensure its survival. Balance is just another way of death.
Timeliness	Complex systems evolve over time, past behaviors have an impact on the present. For any analysis of complex systems, if the culling time dimension, it is incomplete

These characteristics are the consensus of most scholars and also the basis for the discussion of complexity in this thesis.

2.3 Architecture as a Complex Adaptive System

As an important branch of complexity theory, Complex Adaptive Systems (CAS) theory is the sublimation and crystallization of complex theory. Since its introduction by Holland in 1994, it has attracted widespread attention in the academic community and has been widely used in economic systems, ecosystems, and social systems. Holland (1994) summarizes the seven basic characteristics of the complex adaptive system, including four characteristics (aggregation, nonlinearity, flow, diversity) and three mechanisms (identification, internal models, building blocks). These seven basic characteristics are the necessary and sufficient conditions for complex adaptive systems. Each complex adaptive system has these seven basic characteristics and the complex system with these seven basic characteristics can be defined as a complex adaptive system (Holland & Wolf, 1998). Table 2.3 shows the basic characteristics of architecture based on seven basic characteristics (Holland, 1994), these characteristics of architecture demonstrate architecture as a complex adaptive system.

Table 2.3 The basic characteristics of architecture as a complex adaptive system

Number	Characteristic	Contents
1	Aggregation	The formation and development of architectures depends on the gathering of people. From the early settlements to small

		villages to small towns, the direct driving force for the generation and development of architecture is the spatial agglomeration effect of human beings. The gathering of people produces new architecture functions, the industrial aggregation brings huge scale effects, etc. These are the aggregation characteristics of architectures (Roth, 2018).
2	Nonlinearity	Non-linear claims that whole is greater than sum of its parts. During exploring the nature of architecture, scholars have increasingly found the weakness of rationalism and reductionism in solving complex architecture problems, the traditional linear thinking does not apply to complex architecture systems. The nonlinear and complex nature of architectures has been increasingly recognized (Jiang & Adeli, 2008)
3	Flow	The essence of flow is the exchange of matter, energy and information between subjects. It also has the characteristics of flow within architectures. Research on spatial forms such as capital flow, logistics, people flow and information flow has been widely taken attention. An important characteristic of flow is its circulating effect, it is easy to understand from the perspective of people flow, the circulating flow of people is a dynamic architecture space system. This also provides a new theoretical basis for us to build a green architecture (Pallasmaa, J, 2007).
4	Diversity	In the architecture system, diversity can be seen everywhere. From a micro perspective, architecture contains various functions, different organizational structures, etc. From a macro perspective, each architecture

		has its own development characteristics and there are not same architectures. This diversity constitutes a reasonable architecture system (Ubarretxena Belandia & Engelman, 2001).
5	Identification	Identification is the basis of the interaction of the body. From the microscopic point of view, coordination between different architecture space rely on identifying different functions. From the macro perspective, the architecture function area division is also based on the identity of the architecture's resources.
6	Internal Models	The 'collage architecture' theory (Johnson, 1994) holds that architecture design has never been carried out on a piece of white paper, but on the background of the architectures produced by historical memory and progressive architecture accumulation. This is the architecture's development process and learning process of past experience, as well as decision making for the future of architecture. The study of the internal model of architecture will contribute to the development of architecture.
7	Building Blocks	Building blocks are the basic components of the internal model. The diversity of internal models comes from the various combinations of building blocks. This is similar to the different development modes of architectures in different stages, some architecture can skip some stages to form a leap-forward development, this is caused by the different combinations of architecture blocks (Frazer, 1995).

2.4 Characteristics of Viewing Architecture as a CAS

As mentioned above, we argue that architecture is best construed as a complex adaptive system (CAS). This system is radically different from the static system of architecture as it involves the following features:

1. Architecture as a CAS consists of multiple agents, these agents interact with each other.
2. Architecture as a CAS is adaptive, architecture design is conducted under the background of past architectures, current and past interactions together feed forward into future architecture.
3. Architecture is the consequence of competing factors ranging from architect’s personal experience to social motivations.
4. The structures of architecture emerge from art, culture, policy, economic, human, function, technique and environment.

Consequently, the advantages of viewing architecture as a CAS is that it provides us with a unified account of seemingly unrelated architecture phenomena and it is believed that the development of architecture is a process of adaptive evolution (Holland, 1995, 1998; Holland, Gong, Minett, Ke, & Wang, 2005). To be more specific, architecture as a CAS contains multiple agents interacting with each other so that it has the ability of self-regulating as the environment changes. These agents adapt to the environment (including the natural environment and the human environment) in order to continue itself, this is the commonality of adaptation. On the other hand, the adapting process is adapting the agents’ response to changes in environmental conditions. With different agents and different environmental conditions, the degree and process of adaptation are also changing, this is the diversity of adaptation (Giacomoni，Kanta，Zechman, 2013).

In short, we have understood the commonality and diversity of agents’ adaptation in architecture as a CAS, yet how to utilize the characteristics in architecture remains a question. In this thesis, we propose a new design thinking approach for creative architecture design, that is ‘Concept Topology Optimization’.

Chapter 3 New Design Thinking Approach: 'Concept Topology Optimization'

3.1 Content of Topology

As a branch of geometry, topology involves a lot of content, some of which have been translated into the field of architecture, and become the theoretical support for the development of architectural design. The term 'topology' first appeared in Listin's paper 'Preliminary Study of Topology' in 1848, and this new field of geometry was originally defined as 'location analysis'.

In the famous book 'What is Mathematics', Courant and Robbins wrote: 'Topology is about the study of the geometry losing its original metric and projection characteristics under severe deformation'. Thus, the topology in mathematics evolved into: 'Study the nature of geometric shapes that remain constant under continuous deformation (so-called continuous deformation, which allows deformation such as stretching, twisting, and rotation, but not cutting and bonding).'

Topology is born out of geometry, generalizing some of its concepts, and abandoning some of the structures that appear in it. Literally, the term "topology" means research on configuration and positioning, topology. Study the shape and its properties, deformations and the mapping between them, and the configuration that combines them. Figure 3.1 shows the Topological change process from coffee cup to bagel. This chapter only covers the content related to 'Concept Topology Optimization'.

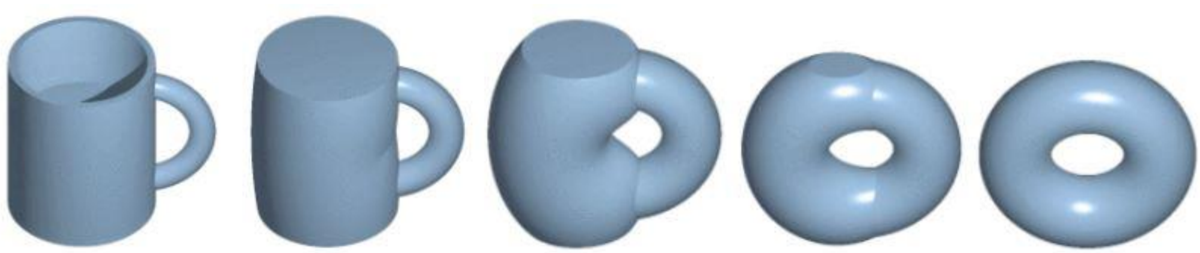

Figure 3.1 Topological change process from coffee cup to bagel

3.1.1 Graph theory

The topology in mathematics goes back to the Seventh Bridge Problem of Königsberg (Shields, 2012) in 1736 shown in Figure 3.2 Euler (Euler, 1953) abstracts the problem into a mathematical structure, that is, a diagram of the links between nodes. This structure is called a "graph". It has the characteristics of topology: without changing the nature of the chart, as long as the connection between the nodes does not change, the shape of the chart can be arbitrarily distorted and deformed, which is independent of the position of the node and the straightness of the connection. It can be seen that what is important is the way the chart is connected, not the form itself, which is the original meaning of topology.

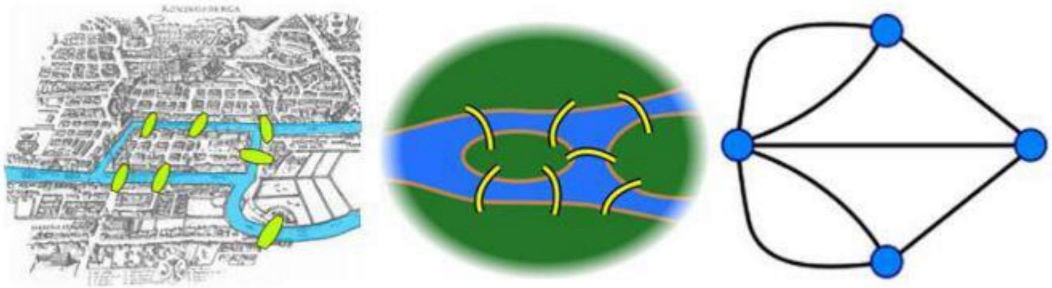

Figure 3.2 Seventh Bridge Problem (Shields, 2012)

The application of graph theory is extremely extensive. Anything involving array-and-combination optimization problems will inevitably use the knowledge in graph theory, such as communication codec, matrix operation, task assignment, GPS path planning, and so on. In the field of architecture, the commonly used functional bubble diagram principle also comes from graph theory, abstracting the specific functions in the building into points, the degree of connection between functions is represented by different lines, and the relationship between functions is represented by graph theory. The methods are translated into diagrams for analysis and optimization. Early modernism limited the basis of architectural form formation to functional relations and became a representative of functionalism. However, the influence factors of urban environment and construction are becoming more and more complicated, and the generation of graph theory is no longer limited to the organization of functions. Therefore, the role of graph theory in construction is becoming more and more obvious.

3.1.2 Topological embedding

Embedding is an action in mathematics. As an important part of topology, embedding is to consider how to put the topological space into the interior of the other party. Embedding one network A into another network B means to refer to each node in A. Mapping 16 to B nodes, this is embedding, which studies the local topological properties unique to Euclidean closed subsets.

The Klein bottle is typically embedded (Krogh, Larsson, Heijne, G & Sonnhammer, 2001). The figure 3.3 shows how to bond the Klein bottle together: first bond the left and right sides of the square into a cylindrical surface. Then, when it is intended to bend the circumference of the top end of the cylindrical surface and the circumference of the bottom portion by bending the cylindrical surface like a torus, it is found that the arrows of the two circumferences do not match. The only way to match the arrows in three-dimensional space is to allow the cylindrical surface to pass through itself, so that the two circumferences can be successfully bonded together so that the arrows match. However, the real Klein bottle has no circumference that intersects itself, and this object has intersecting circles. In fact, in three-dimensional space, the real Klein bottle does not exist. In the four-dimensional space, can it Realized by self-intersection.

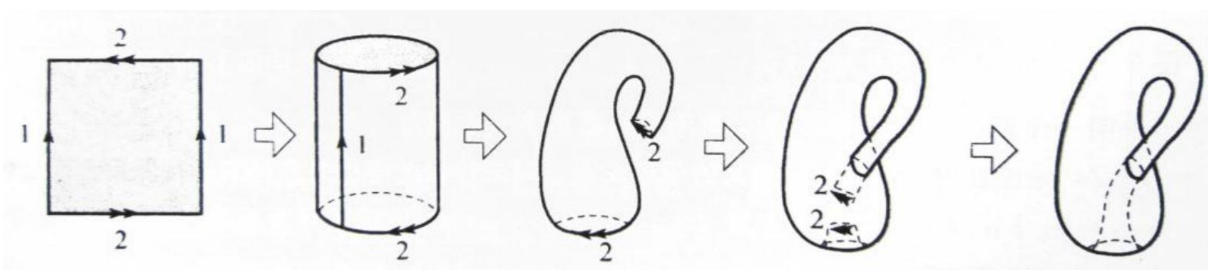

Figure 3.3 Klein Bottle (Lawrencenko & Negami, 1997)

3.1.3 Knot theory

Knot theory (Crowell & Fox, 2012) is a branch of algebraic topology that studies ‘How to embed several rings into 3D Euclidean space’. Mathematically, the Knot has a more rigorous definition. The knot is a closed curve segment in three dimensions, which produces various orderly interlaces in space. C.F. Gauss (Dunnington, Gray & Dohse, 2004) introduces the number of surrounds between closed curves, which is one of the basic tools of the knot theory. It can perform rigorous mathematical descriptions of knots, and computer tools can distinguish between equivalent or non-equivalent knots. “The most basic name for a junction is Ck, where C is the effective number of interlaces, the least number of interlaces projected by the junction on the plane, and k is the junction with a different topology. C is a topological invariant and two have different C values. The knot must be non-equivalent." No matter how to solve or make continuous changes (not cut), it is unable to turn one of them into another. Not equivalent to two topologies. "No matter how to solve or make continuous changes (not cut), it’s unable to turn one of the knots into another. Figure 3.3 shows the common topology knot types.

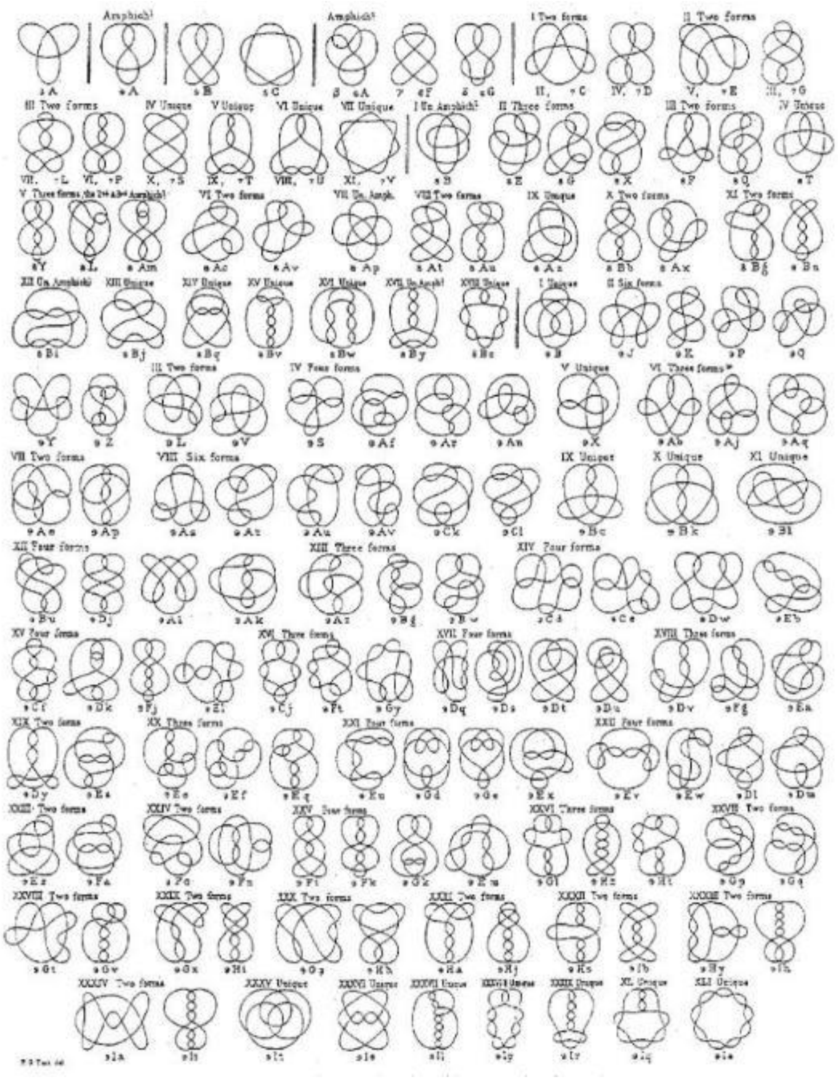

Figure 3.4 Common Topology Knot Types (Alexander, 1928)

The "knot theory" is a proposition that has been extensively experimental in architecture. As a branch of topology, no knots can be formed in a two-dimensional plane space, and in a four-dimensional or higher-dimensional space, the knot becomes It is very complicated and difficult to describe. Therefore, in the field of architecture, it is more important to consider three-dimensional objects. In topology, more is to explore the knot of the closed curve. In many cases, the curve of the knot is used as the building streamline to complete the organization and series of space, which is the premise of studying the variable type of space. The knot is not the property of the curve itself, but the illustration and result of the curve motion. Just as the relationship between the ring and the hole, the extension deformation of the kink must also exclude the cut and adhesion allowed by the general topological transformation.

3.1.4 Topological connectivity

Connectivity is the concept of topology, defined in mathematics is "Set X to be a topological space. If there is no set in X that is both open and closed, then X is said to be connected. It is a topological invariant property of the topological space. If there is a homeomorphic map between them, one of the spaces is connected, and the other space is also connected." The response on the graph is shown on Figure 3.4 & Figure 3.5.

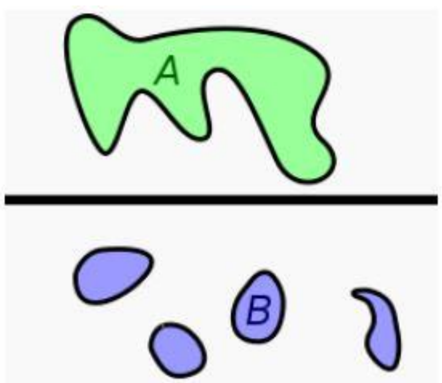

Figure 3.5 Connected and Disconnected Subspaces of R^2

The space A above is connected, and the space B below is not connected.

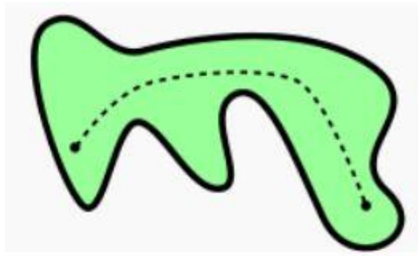

Figure 3.6 Connected Subspaces of R^2

This subspace of R^2 shown in Figure 3.5 is connected because any two points can be plotted in a way. Bruno Zevi's (Zevi & Gendel, 1974) seven basic principles of modern architectural language have a “space-time continuity” that is similar to connectivity in mathematical concepts, and is intended to express the continuity and extension of architectural space between dimensions. The continuous and extended space is different from the flow space advocated by Mies (Johnson, 1978). Compared with the flow space, it represents a more profound meaning. The liquidity it exhibits is not only reflected in the relationship between space, but also in the space unit itself. Morphologically. In the field of architecture, connectivity is more manifested in the connection of space or the organic organization of the building group.

3.1.5 Manifold

A manifold is a structure (topological, smooth, coherent) object that has an n-dimensional space or some other vector space locally. A manifold is a space that has a local Euclidean space. In fact, Euclidean space is the simplest example of a manifold. A typical manifold can be formed by bending and adhering a number of straight sheets. Manifolds are used in mathematics to describe geometric shapes, which provide the most natural stage for studying the variability.

“Manifold” is the central topic of topology development since the 1950s, and it is about geometry. The study of the properties of surfaces and generalized surfaces is roughly a generalization of the concept of surfaces in any dimension. In topology, there are the following definitions: “Connected one-dimensional manifolds are called curves; connected two-dimensional manifolds are called surfaces.” However, manifolds can have any dimension, such as: a line of circles (one dimension) And all rotations (three-dimensional) in three-dimensional space. An example of rotating the composition space shows that the manifold can be an abstract space.

3.2 Significance of Topology

Compared with traditional Euclidean geometry, the research objects of topology and the research methods presented are quite different. Table 3.1 shows the difference between Euclidean geometry and topology.

Table 3.1 Difference between Euclidean geometry and topology

	Research Object	**Space Concept**	**Research Content**	**Form of Expression**
Euclidean geometry	Straight line, polygon, polyhedron	Static, eternal, closed space view	The combination of point and line and quantitative research	Combination of simple geometric shapes
Topology	Network, surface, void, knot	Movement, change, continuous view of space	Characteristics of objects in continuous deformation	Folded, wrinkled, twisted

3.3 Architectural Topology

Topology is a branch of mathematics, a research method and a deep way of thinking. The introduction of topological thinking into architectural design creates architectural topology. The topology of architecture is to study the characteristics of the architectural form and its evolution law by using the theory and method of topology, and also to explore the topological evolution and process of the shape between the various stages of architectural design. The research of this discipline helps to strengthen the logic and richness of architectural form change and also has theoretical guiding significance for the relationship between architecture and environment.

Architectural topology studies the topological homeomorphism and non-homeomorphism between different morphologies in order to find a variety of alternatives that meet the same design requirements. Combining the four types of topology changes in topology, we classify the evolution process from the functional analysis diagram (bubble map) to the final scheme into four levels in the architectural design process, each level has more varied deformation than the previous level. Here we take the residential design as an example to elaborate on the influence and inspiration of topological deformation theory on architectural design.

3.3.1 Level 1: From Bubble Map to Architectural Map

This level of morphological change belongs to the primary stage of topological deformation. In this change of form, only the geometrical changes occurring between the geometric shapes such as a circle and a square change the spatial geometric form before and after the change, and the relationship (functional connection) between the spaces remains unchanged. The transformational inheritance relationship can be clearly seen between the forms. For example, in architectural design, the bubble diagram - through elastic changes into an equivalent rectangular floor plan (shown in Figure 3.6.

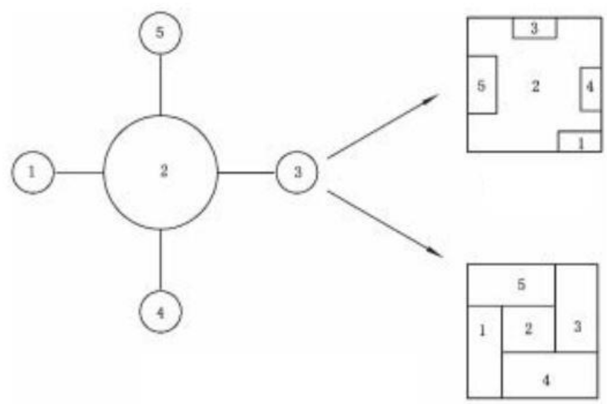

Figure 3.7 Example of Bubble Map to Architectural Map

3.3.2 Level 2: Differential Homomorphic Changes in Architectural Form

It means that some or all of the previous architectural drawings can undergo elastic changes such as stretching, squeezing, bending, twisting, enlarging and shrinking. The shape before and after the change should remain intact. There can be no adhesion at any two points in the form (from two points to one point), or to rupture (split from one point to two points), causing cracks or cracks in the building form. The post-form maintains an attribute consistency with the native form. It is therefore called differential homeomorphic variation of topological properties. Figure 3.8 is an example of differential homomorphic changes in architectural form.

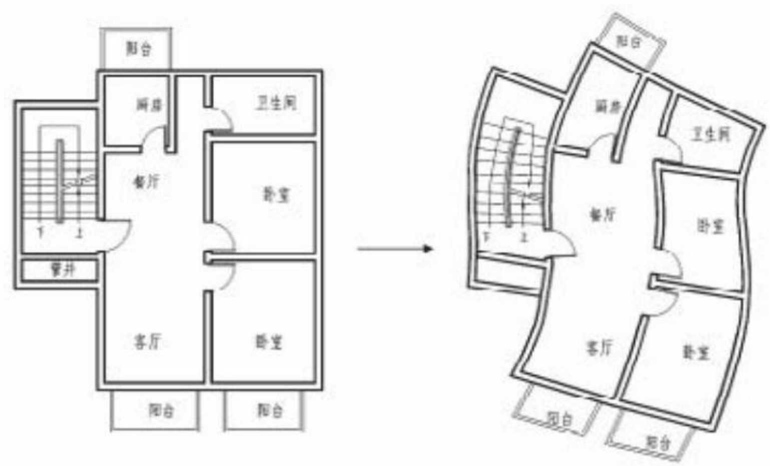

Figure 3.8 Example of Differential Homomorphic Changes in Architectural Form

3.3.3 Level 3: Homeomorphic Changes in Architectural Form

This topological change is the same as the second level of topological change, but it is higher than the degree of deformation, the magnitude of the shape change is larger, and even the composite change of several forms of deformation. This change can cause the form to wrinkle or pull the plain creases. When the same morphological change occurs in the building form, it should also be ensured that no merging between the two points of the building form or splitting from one point to two points causes the building form to form adhesions and cracks, and the form before and after the change remains relatively clear. We can see the transformation and inheritance relationship between the forms, which belongs to the intermediate stage of architectural form change. This level of deformation also has morphological changes in stretching, extrusion, bending, rotation and combinations. Figure 3.9 is an example of homeomorphic changes in architectural form

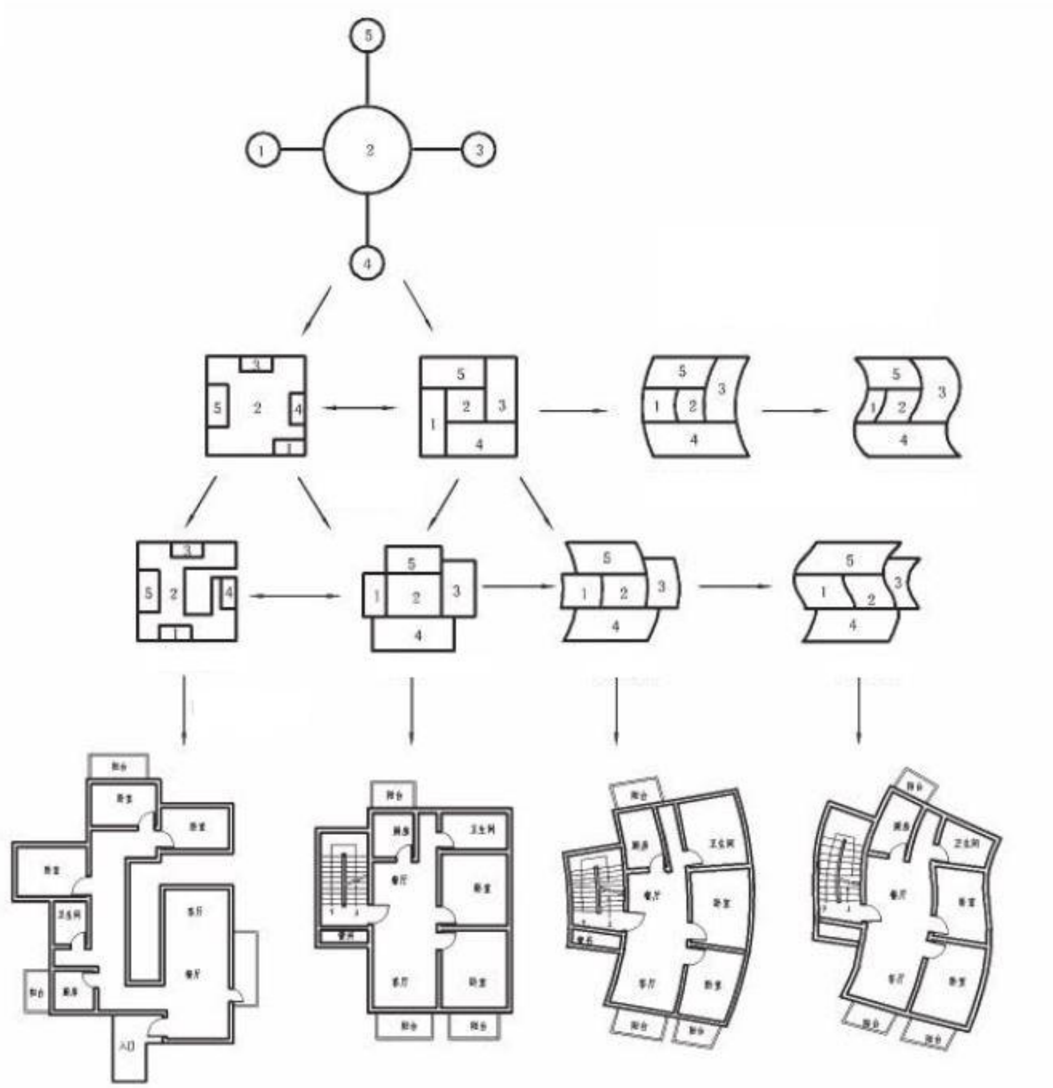

Figure 3.9 Example of Homeomorphic Changes in Architectural Form

3.3.4 Level 4: Non-Homeomorphic Changes in Architectural Form

Non-homologous changes refer to the adhesion or rupture of an object's shape under the action of external forces, resulting in new structural forms and the emergence of new structural types. This level of morphological change is an advanced stage of topological change. When the deformation of the building's figure occurs, the functional relationship between the main spaces inside the building does not change, but only those parts of the mutation re-establish the relationship with the original form, thus causing certain changes in the architectural form and generating new forms. Figure 3.9 is an example of non-homeomorphic changes in architectural form.

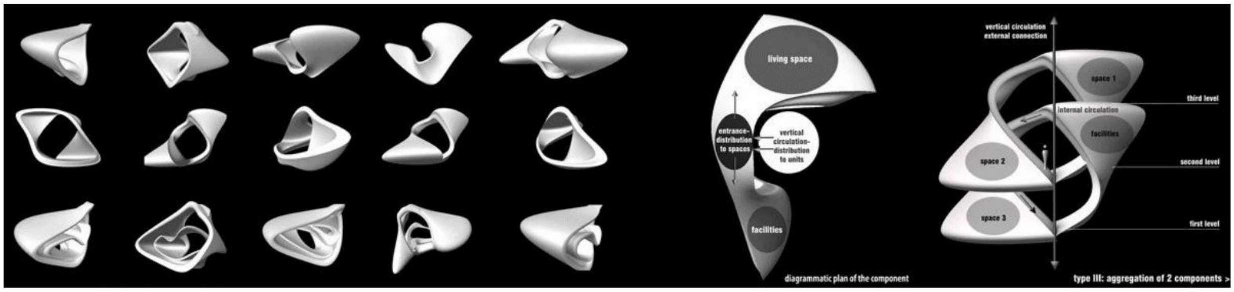

Figure 3.10 Example of Non-Homeomorphic Changes in Architectural Form
(Xing & Zhenyu, 2014)

3.4 Concept Topology Optimization for Architecture as A Complex Adaptive System

Prior design creativity studies have showed that new design concepts arise from the analogy (Weisberg, 2006; Linsey et al., 2012), synthesis, blending (Taura and Nagai, 2012), or more general forms of creative transformation of existing knowledge or concepts (Hatchel and Weil, 2009). Recently Youn et al. (2015) show empirical evidence from patent analysis that modern inventions primarily arise from the combination of existing technologies rather than the introduction of new technologies. In this thesis, we classify these methods for creative design as 'Concept Linear Optimization', they are easy to understand and useful in relatively simple design tasks. However, for architecture as a CAS, these methods may not be the most suitable optimal solutions.

As mentioned above, architecture as a CAS is adaptive which consists of multiple agents interacting with each other, it led to the complex characteristic of architecture. It's believed that there isn't any complex system can be too complicated to touch, and humans have come to face the complex system and overcome the complex problem. Complex systems may come from a very simple nonlinear equation or a simple set of rules (Corrado, 2019). Figure 3.10 shows an example of this hypothesis: Mandelbrot Set has amazing levels of complexity but it arises from extremely simple mathematics: – f(z) = Z2 + C. Corresponding to this, topology is a discipline that studies the invariant properties of geometry or space after continuous change (Munkres, 2014), that is the main reason why we present 'Concept Topology Optimization' for architecture design as a complex adaptive system in this thesis.

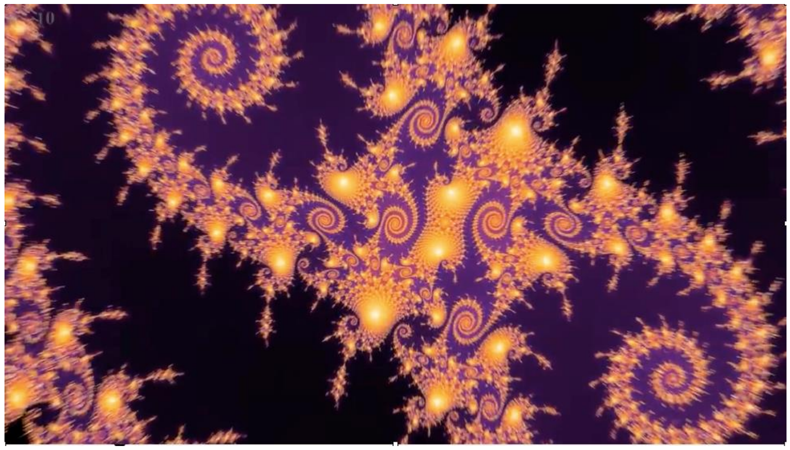

Figure 3.11 Mandelbrot Set

(Figure Source: https://www.youtube.com/watch?v=PD2XgQOyCCk)

3.4.1 Definition of Concept Topology Optimization

Concept Topology Optimization (CTO) is an interaction-based design approach that optimizes concept with a given ground structure or mixed ground structures, for the goal of maximizing the performance of architecture as a complex adaptive system. Figure 3.11 shows the basic model of Concept Topology Optimization.

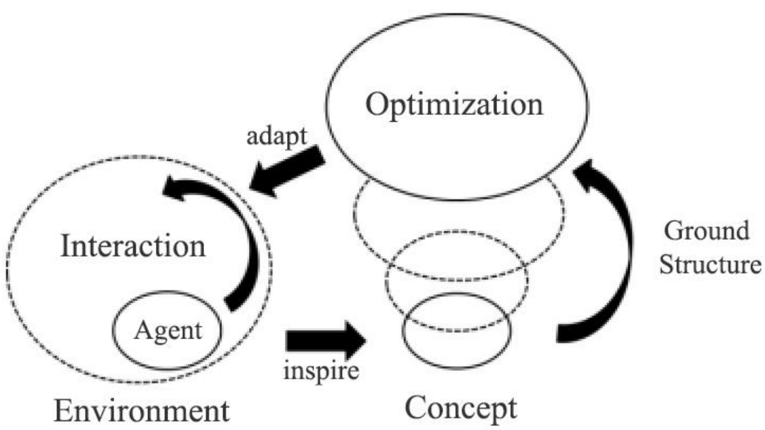

Figure 3.12 Model of Concept Topology Optimization

3.4.2 Three levels of Concept Topology Optimization

An 'Design Agent' is an actor that has the capacity to adapt to their state to some change within their environment. As an analogy to the application of topology in architecture form design, we suppose 'Topology Optimization' can also be divided into three levels in CTO:

1. Differential Homomorphic CTO: Optimization does not change the original concept but requires the ability of abstraction and review. (Case study 1 is an example)

2. Homomorphic CTO: On this level, optimization includes analogy, synthesis, blending or more general forms of creative transformation of existing knowledge or concepts. After the topology optimization, the changing inheritance relationship can still be found in the new concept and the logic process of the concept optimization can be clearly seen. (Case study 2 is an example)

3. Non-homeomorphic CTO: This level is accompanied by the tearing, cutting, and blocking on the deformation of the second level. This optimization destroys the overall structure of the original concept to some extent, belongs to the scope of emergence. (Case study 3 is an example)

3.5 Reasons of Conducting the Three Case Studies

Case study is defined as an intensive study of a single unit with an aim to generalize across a larger set of units (Gerring, 2004). Researchers describe how case studies examine complex phenomena in the natural setting to increase understanding of them (Hamel, 1993; Yin 2003). Indeed, when describing the steps undertaken while using a case study approach, it allows the researcher to take a complex and broad topic, or phenomenon, and narrow it down into a manageable research question(s). By collecting qualitative or quantitative data about the phenomenon, researcher can achieve a more in-depth insight into the phenomenon (Heale, 2018).

Therefore, in this thesis we conduct three case studies to examine Concept Topology Optimization design approach in architecture to increase understanding of it. Architecture is a too complex and broad topic (Fraser, 2013), thus we need to narrow it down into manageable research questions. In addition, we acknowledge architecture as a complex adaptive system (CAS), thus these 'manageable research questions' need to be related to the scope of complex adaptive system.

Complex adaptive systems are dynamic systems able to adapt in and evolve with changing environments and a CAS closely linked with other related CASs making up an ecosystem. Within such a context, change needs to be seen by co-evolution with all other related complex adaptive systems, rather than as adaptation to a separate and distinct environment (Chan, 2001). Typical examples of complex adaptive system related to architecture include ecosystems, the human and society (Grove, 2009). As a result, we link these three typical CASs with architecture as changing environments and narrow architecture down into following manageable research questions and conduct 3 case studies:

Case study 1: How to apply Concept Topology Optimization design approach in aiding in architecture location design that make architecture more environmental to local ecosystems?

Case study 2: How to apply Concept Topology Optimization design approach in developing a new method for more creative human-centered architecture space design?

Case study 3: How to apply Concept Topology Optimization design approach to solve building workers' safety problems in building construction?

The purposes and characteristics of each case studies are as followings:

Case study 1 aims to use the first level of CTO to aid in the expo-architecture location design and make architecture more environmental to local ecosystems in LinGang wetland park. In this case study, building is the design agent, local ecosystems is the environment and SWAT model is the ground structure.

Case study 2 aims to use the second level of CTO to developing a new method for more creative human-centered architecture space design. In this case study, human is the design agent, 'field' for human is the environment and Su-field analysis model is the ground structure.

Case study 3 aims to use the third level of CTO to solve building workers' safety problems in building construction. In this case study, worker is the design agent, construction environment is the environment and BP Neural Network Algorithm is the ground structure.

3.6 Relationships Among the Three Case Studies

All the three case studies apply CTO design approach in architecture to increase understanding of it. Figure 3.13 shows the relationships among the three case studies.

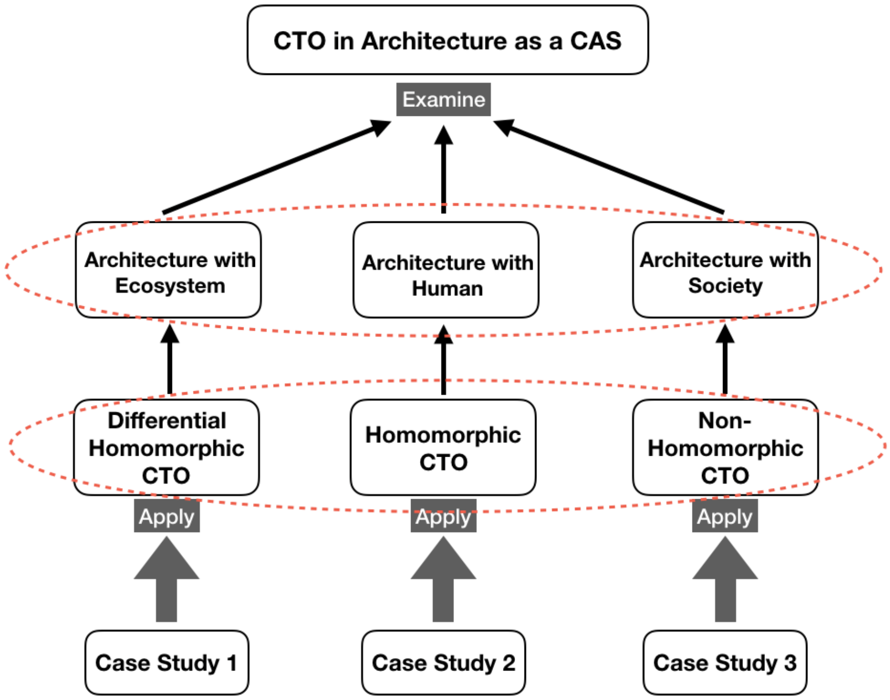

Figure 3.13 Relationships Among the Three Case Studies

CTO design approach has three levels and three typical CASs with architecture as changing environments are elucidated in chapter 3.5, thus we conduct three case studies that each case study utilizes one level of CTO design approach in architecture with one typical related CAS as a changing environment. Therefore, these three case studies constitute a complete research which examines Concept Topology Optimization design approach in architecture as a CAS.

Chapter 4 Case Study1: SWAT Model-Based Ecological Expo Architecture Location Design

This chapter is from the following journal paper:

Shen, T., Nagai, Y., & Chen, X. (2018). Ecological Environment Based on the Expo Architectural Design Project. *Ekoloji*, *27*(106), 1-9.

We believe that rather than being regulated by technology, architects should exploit it so as to promote the basic needs of ecology. In this chapter, we first introduce the concept 'Ecological Architecture', then we propose five design principles for ecological architecture design. Furthermore, based on CTO design thinking approach, we present a method of using Soil & Water Assessment Tool (SWAT) model to aid in the location design of the expo architectural design project on LinGang wetland park, Figure 4.1 shows the model of CTO in case study 1. In this method, expo building is the design agent, wetland park is the environment and SWAT model is the ground structure.

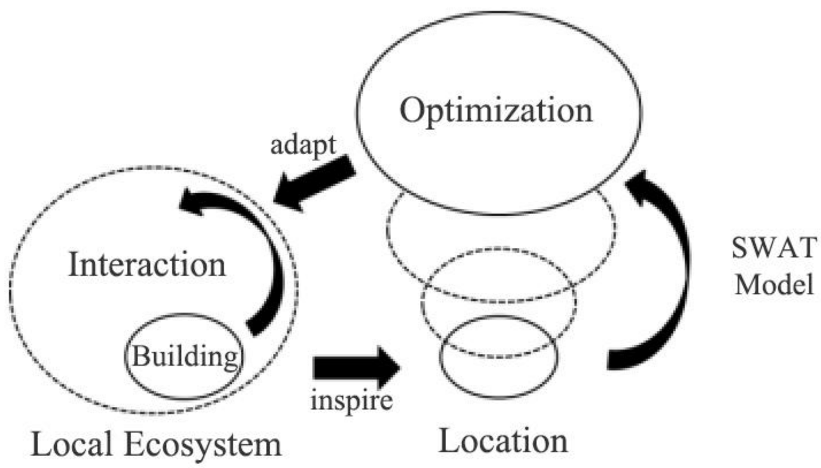

Figure 4.1 Model of CTO in Case Study1

4.1 Contents of Ecological Architecture

The ecological architecture refers to the integration of ecological ideas into the process of architectural design (Qimin, 2000). Ecological architecture fully respects the characteristics of the coordination relationship between human, nature and the building itself, also considers the characteristics of energy-saving, low-cost, environmental protection and ecological balance (Anker, 2005). First of all, the ecological architecture design adopts advanced architecture technology to make full use of renewable resources such as solar energy and wind energy, which greatly reduces the consumption of non-renewable resources in buildings. At the same time, ecological architecture can also use the biological action and physical principles to satisfy the requirements of ventilation, lighting and insulation inside the ecological building, so that to reduce the energy consumption in the ecological building operation process and achieve the effect of energy saving and emission reduction. Secondly, the design of ecological buildings focuses on the use of recyclable renewable resources which can not only control the cost of the project, but also make full use of the building materials, effectively control the construction waste and reduce the adverse effects of ecological buildings on the environment (Sheng, 2007).

4.2 Four Sub-Concepts for Location of Ecological Expo Architecture

In this case study, we abstract and review the concept of location for an ecological expo architecture in LinGang wetland park and four sub-concepts are presented: ‘environmental’, ‘regional network’, ‘traffic accessibility’ and ‘building scale’. Among these four sub-concepts, ‘regional network’, ‘traffic accessibility’ and ‘building scale’ are easy to satisfy because they are well-defined concepts but ‘environmental’ is ill-defined. Therefore, making quantitative analysis of ‘environmental’ is the major creativity in this case study, to achieve that, we firstly analyze the interaction between building and wetland park is water, then we use SWAT Model to make quantitative analysis of water quality for designing the expo architecture location.

4.2.1 Environmental

According to the preservation of natural wetland environment, urban wetland parks divide the park wetland into three different ecological protection levels. The first one is the core conservation level in urgent need of protection; the second is the buffer protection level that is relatively fragile but allows a small amount of scientific activities; and the last is the open level that can undertake a certain degree of man-made construction and activities. Through wetland environmental assessment, the natural environment of wetland is divided into different levels, and the basic requirements of distinguishing types, key protection and rational development in the process of wetland park protection are realized (Laughlin Fang et al., 2017).

On the basis of these three ecological levels, according to their geographical location, the wetland park has basically formed four geographical areas: peripheral area, open area, buffer zone, and protected area. According to the different layers of wetland environment in each geographical area, a reasonable artificial building and environment layout can be carried out. The protected area is an area in urgent need of wetland environment conservation. It is necessary to establish scientific observation points to record and pay attention to the conservation while ensuring no human disturbance. The buffer zone allows a small number of man-made facilities and simple buildings to ensure the smooth progress of environmental experiments and cultivation. In this case, the functional buildings in the park can only exist in the open area in the ecological open level. Between the area and the surrounding area, buildings with management, service and reception and many other functions are constructed, to meet the management and reception needs of wetland parks.

4.2.2 Regional Network

In the urban planning, each area and function of the city are divided. The regional positioning of the ecological exposition building of the wetland park constructed by the natural wetland environment is not only determined by the location of the natural wetland, but also guided by the network in the overall planning of the park. Therefore, the network park regional standard positioning is also the basis for planning and site selection of eco expo building in wetland park (Páez, 2017). Wetland Park ecological exposition building is integrated with wetland tourism, urban culture, commercial entertainment and other new industrial functions, forming a multi-functional space system to improve public cultural benefits while providing a recreational and leisure environment.

The network formed by the planning and design of leisure, recreation, commerce and potential axis in the overall planning of wetland park is regarded as a development direction of wetland ecological economy in the future. In different construction sites, the expo architecture can cooperate with various buildings, structures, scenic spots and natural landscapes to form a network according to the tour path, amusement path and leisure business path in the planning of the wetland park. The objective is to find the most suitable site for the expo architecture in the existing park network, achieve the best park tour effect, and increase ecological economic benefits. According to the location and state of the natural terrain, the architectural layout in this network presents a trend of agglomeration or diffusion. Sometimes, because of the limitation of terrain and the need of overall planning, many types of buildings are centralized; sometimes, due to the dispersal of the ecological hierarchy area, the buildings also have discrete layout and it is combined through the tour path.

4.2.3 Traffic Accessibility

The site selection of the exhibition building is a very important link in the planning and architectural planning of the wetland park. The proper site selection not only ensures the normal operation and social benefits of the exhibition building itself, but also relates to the coordinated development of all public buildings in the wetland park and the operation and development of the whole park (Liu and Ping, 2018).

There should be convenient public transportation around the location of the expo buildings to ensure the accessibility of traffic. Expo building is a public building with mass and cultural service that needs to receive a large number of audiences. But it is different from those buildings with relatively fixed users, such as education and office buildings. Expo building needs to gather the active participation of audiences through its own attraction. This self-attraction except the splendid exhibition of the eco-exposition building itself, also includes the city traffic where it is located. Convenient traffic accessibility is the basic condition for attracting visitors and facilitating the transportation of goods.

4.2.4 Building Scale

The scale of the exhibition building can be divided into super large, large, medium and small according to the total exhibition area within the base, as shown in *Table 4.1*. The level of the exhibition hall can be divided into Class A, Class B and Class C according to the exhibition area, as shown in *Table 4.2*. According to the overall planning basis of the park, building scale positioning based on the land conservation as the main design principle is very important to control the impact of man-made environment on natural wetlands (Deng et al., 2016).

Table 4.1 Scale and level of expo buildings

Building scale	Total exhibition area S (m^2)
Super large	S>100000
Large	30000<S≤100000
Medium	10000<S≤30000
Small	S≤10000

Table 4.2 Scale and level of exhibition hall

Level of exhibition hall	The exhibition area S of exhibition hall (m^2)
Class A	S>10000
Class B	5000<S≤10000
Class C	S≤5000

Ecological protection is one of the most basic responsibilities of wetland parks. If buildings are built in wetland environment without attention to land conservation, it will cause too large construction scale, which is not practical and also leads to many environmental problems, such as blocking biological habitat paths, producing a large number of building noise and waste pollution, and destroying the overall natural landscape (Merrington et al., 2017; Zeng et al., 2016). At present, the problem of land conservation has been noticed in the exhibition buildings of wetland parks.

Taking several domestic exhibition buildings of wetland parks as examples, the chart analysis shows that, except the exhibition hall of Hong Kong Wetland Park, other parts all occupy less than 1% of the total area. The coverage proportion of exhibition buildings in Hongkong Wetland Park, XiXi Wetland area, Shanghai Dongtan Wetland Park, Beijing Yeyahu Wetland Park, Ningxia Shahu Wetland Park, and Nanjing Qiqiao Weng Wetland Park is shown in Fig 4.2, Fig 4.3, Fig 4.4, Fig 4.5, Fig 4.6, and Fig 4.7, respectively.

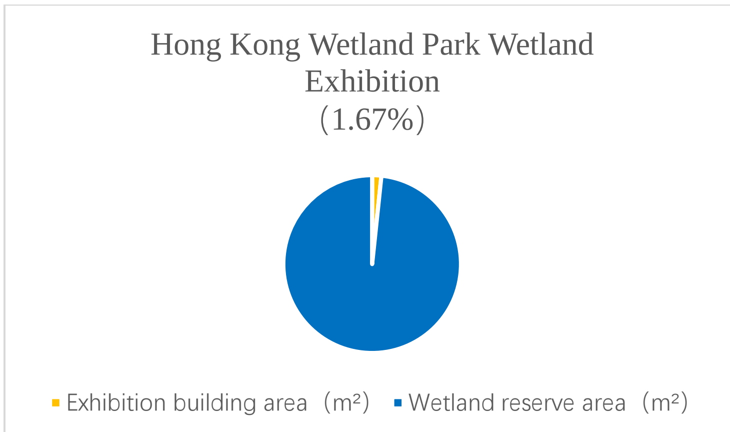

Figure 4.2 Coverage proportion of exhibition buildings in Hongkong Wetland Park

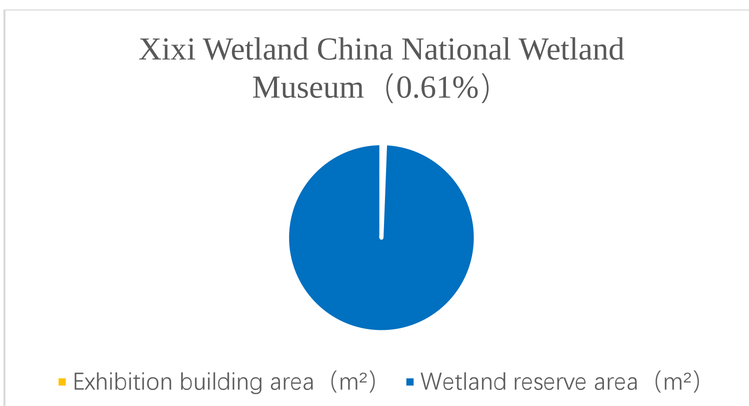

Figure 4.3 Coverage proportion of exhibition buildings in the XiXi Wetland area

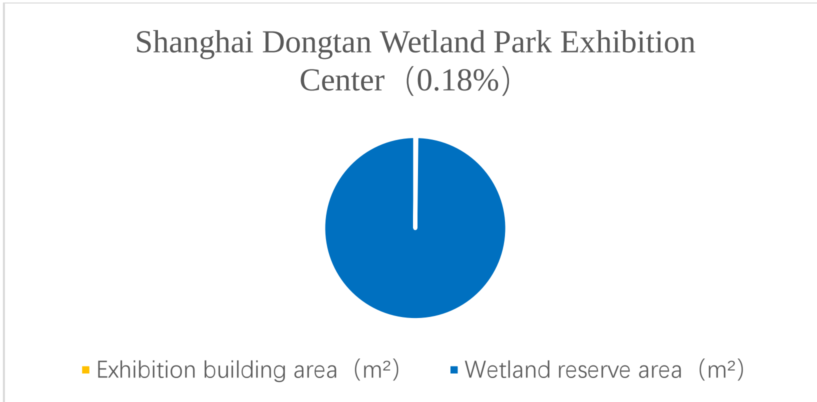

Figure 4.4 Coverage proportion of exhibition buildings in Shanghai Dongtan Wetland Park

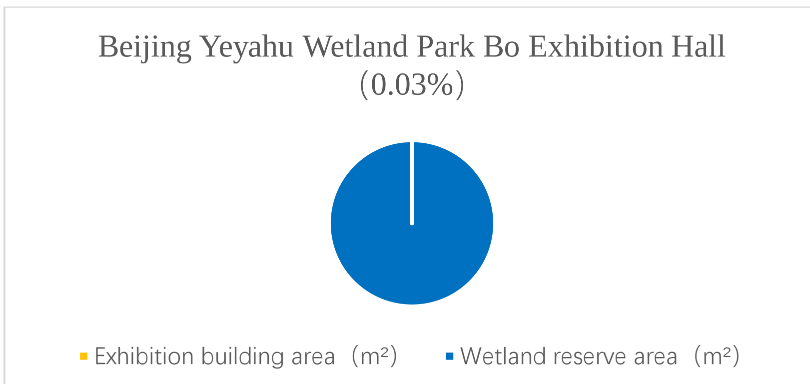

Figure 4.5 Coverage proportion of exhibition buildings in Beijing Yeyahu Wetland Park

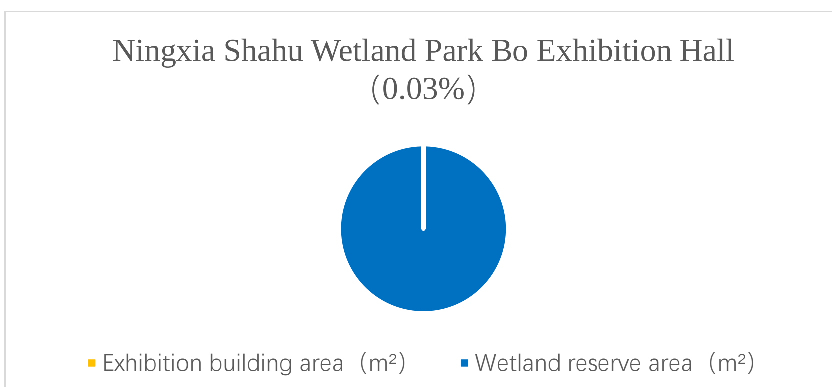

Figure 4.6 Coverage proportion of exhibition buildings in Ningxia Shahu Wetland Park

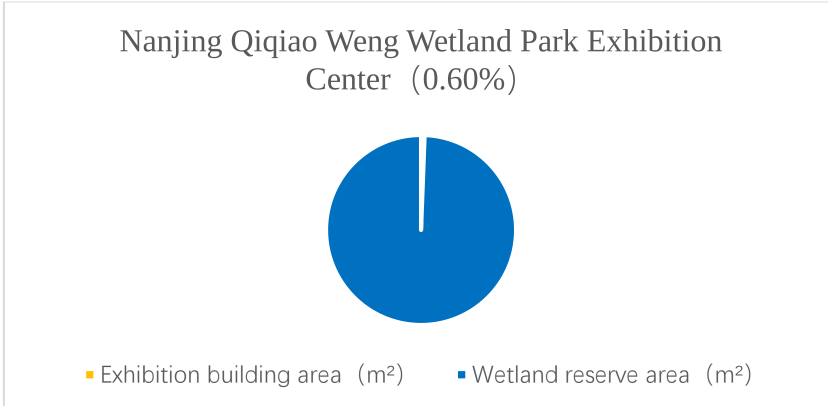

Figure 4.7 Coverage proportion of exhibition buildings in Nanjing Qiqiao Weng Wetland Park

4.3 SWAT Model-Based Ecological Expo Architecture Location Design Method

4.3.1 SWAT Model Construction

The Soil & Water Assessment Tool (SWAT) is a small watershed to river basin-scale model used to simulate the quality and quantity of surface and ground water and predict the environmental impact of land use, land management practices and climate change (Arnold, 1994). To construct the SWAT model, following steps are needed:

Search for basic data: the basic data needed to establish SWAT model include Digital Elevation Model (DEM), land use map, soil type distribution map, soil attribute data and hydro-meteorological data.

Establish model database: the model database is built to produce data that can be directly imported into the SWAT model. Based on the 2017 TM remote sensing images, the land-use grid data are obtained and imported into the model, and the area ratios of different land cover types in the study area were obtained, as shown in *Table 4.3*. According to HWSD, land-soil grid data were obtained and the area ratios of different soil types in the study area were obtained by establishing a soil type index import model, as shown in *Table 4.4*.

Table 4.3 Area ratio of different land cover types in the study area

Land cover types	Land-use Swat code	Area ratio (%)
Housing equipment	UCOM	2.26
No-forest wetland	WETN	0.20
Road traffic	UTRN	20.55
Mixed forest	FRST	49.07
Water	WATR	14.36
Wetland	WETL	13.57

Table 4.4 Area ratio of different soil types in the study area

Soil type	SU-SYM90 code	Area ratio (%)
Water leaching soil	LVj	33.35
Leached soil	Lgs	52.29
Water	WR	14.36

Import database into model and operate: land cover threshold is defined as 5%, soil type threshold is 20%, and slope threshold is 20%. The model is imported and operated and the watershed is divided into 12 hydrological response units.

4.3.2 Parameter Calibration and Verification

There are many parameters in the SWAT simulation. The sensitive parameters of runoff simulation, as shown in *Table 4.5*, are selected for calibration.

Table 4.5 Calibration of sensitive parameters for runoff simulation

Parameters	Parameter code	Parameter range	Parameter value
Runoff curve number	CN2	-0.2～0.2	0.105
Soil evaporation compensation coefficient	ESCO	0.8～1.0	0.8475

Effective field capacity	SOL-AWC	-0.2～0.4	0.3775
Minimum depth threshold for subsurface flow	GWQMN	0～2.0	1.025

The key factors to be considered in parameter calibration include total water balance, time lag or dislocation of rainstorm runoff and the shape of discharge process line. Nash simulation coefficient (E_{ns}), daily average relative error (E_r) and determinant coefficient (r^2) are used to evaluate the simulation results, as shown in Formulas (1) to (3). E_{ns} is used to measure the fitting degree between simulated runoff and measured runoff. The closer it is to 1, the higher the fitting degree between simulated runoff and measured runoff is. It is generally considered that, when E_{ns}>0.5, it meets the requirement of model simulation; Er evaluates the deviation between the simulated runoff value and the measured runoff value, and the smaller the value is, the closer the simulated runoff value to the measured runoff value is. It is considered that when r^2>0.6, it satisfies the requirement of model simulation.

$$E_{ns} = 1 - \frac{\sum_{i=1}^{n}\left(Q_s - Q_m\right)^2}{\sum_{i=1}^{n}\left(Q_s - \overline{Q_s}\right)^2} \quad (1)$$

$$E_r = \frac{\left|Q_s - Q_m\right|}{Q_s} \quad (2)$$

$$r^2 = \frac{\left(\sum_{i=1}^{n}\left(Q_s - \overline{Q_s}\right)\left(Q_m - \overline{Q_m}\right)\right)^2}{\sum_{i=1}^{n}\left(Q_s - \overline{Q_s}\right)^2 \sum_{i=1}^{n}\left(Q_m - \overline{Q_m}\right)^2} \quad (3)$$

In the above formulas, i suggests serial number for analog data; n indicates total analog data; Q_s and Q_m are measured and simulated values of runoff, respectively, m^3/s; $\overline{Q_s}$ and $\overline{Q_m}$ are runoff measurement and simulation average, respectively, m^3/s.

From Formulas (1) to (3) and *Fig.7*, it is known that, $\overline{Q_s}$ and $\overline{Q_m}$ are 45.4465 and 45.4564m^3/s, respectively, E_{ns}=0.972, E_r=0.000219, and r^2＝0.96. The model data are available, and although the simulated values are somewhat different from the measured values, the overall simulation results are good.

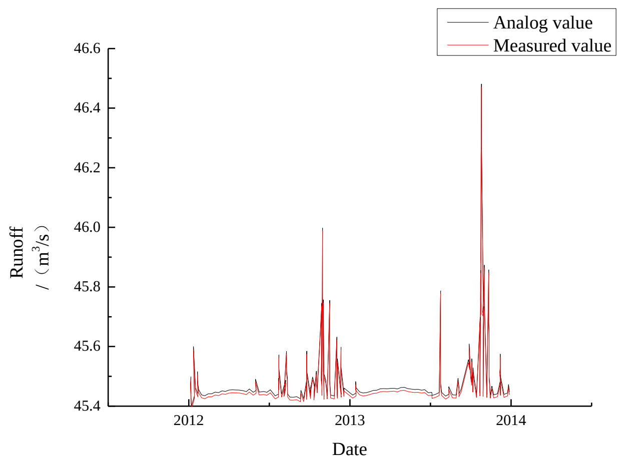

Figure 4.8 Rainfall runoff simulation calibration

Formulas (1) to (3) and Fig 4.9 show that, $\overline{Q_s}$ and $\overline{Q_m}$ are 45.4465 and 45.4539m^3/s, respectively, E_{ns}=0.910, E_r=0.000207 and r^2＝0.90. The change trend of rainfall during validation period is consistent, and the simulation is good, but the runoff simulation value is too large.

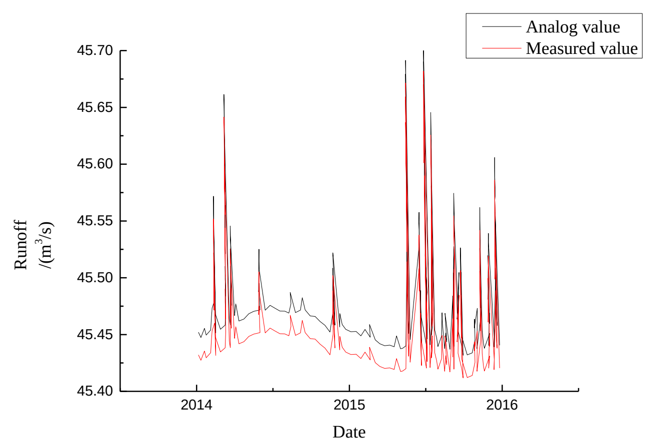

Figure 4.9 Validation of rainfall runoff simulation

4.3.3 Results

Calculation of non-point source pollution in park green space: taking 2017 as an example, the annual rainfall is 756mm and the annual runoff is 1.430 thousand m^3. According to SWAT model, the loss of nitrogen and phosphorus in LinGang Wetland Park is 41 kg and 1.83kg, respectively. From *Table 4.6*, it can be seen that the loss of nitrogen and phosphorus from non-point source is positively correlated with rainfall, that is, with the increase of rainfall, the loss of nitrogen and phosphorus from non-point source increases. The low loss of nitrogen and phosphorus from non-point sources in spring is low due to less rainfall, while the maximum loss of nitrogen and phosphorus from non-point sources in August is related to rainfall and the application of quick-acting fertilizer in summer.

Table 4.6 Nitrogen and phosphorus losses from non-point sources in the study area

Month	Rainfall /mm	Phosphorus loss /kg	Nitrogen loss /10^{-5}kg
January	0	6.79×10^{-5}	0
February	0	7.07×10^{-5}	119
March	6.20	2.57×10^{-4}	0
April	54.50	2.23×10^{-3}	0
May	6.90	2.48×10^{-5}	0
June	76.95	33.53×10^{-3}	75519
July	284.75	368.09×10^{-3}	805752
August	167.60	1195.01×10^{-3}	2712709
September	67.95	207.98×10^{-3}	486662
October	21.80	3.46×10^{-3}	779
November	58.05	12.62×10^{-3}	4061
December	11.55	6.58×10^{-3}	5557

Analysis of pollution capacity of wetland system: water quality monitoring is conducted on the inlet and outlet of the park water, and the monitoring time is 1-12 months in 2017. In order to increase the frequency of water quality monitoring during the flood season, the water quality of the park is monitored once a month in January-March and November-December, twice a month in April-June and September-October, and four times a month in July-August.

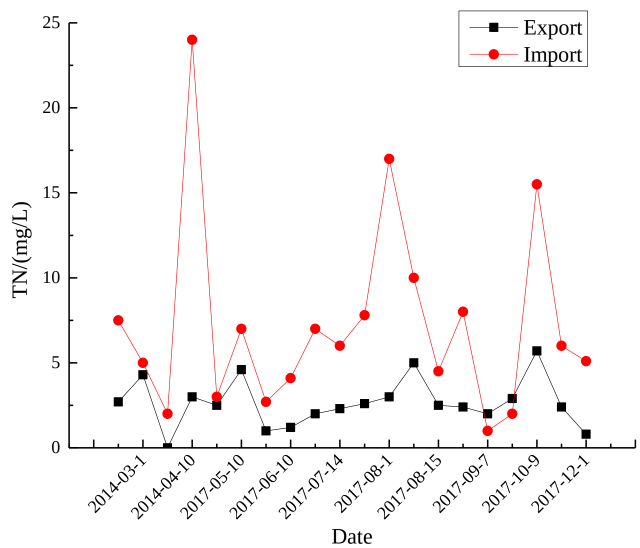

Figure 4.10 Comparison of imported and exported TN in the study area

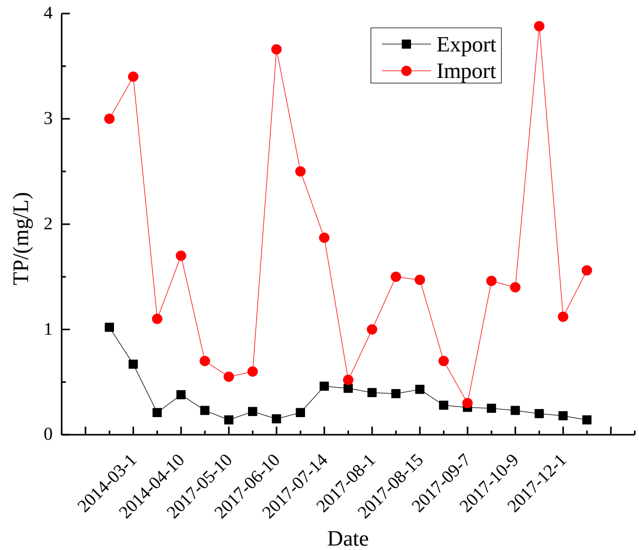

Figure 4.11 Comparison of imported and exported TP in the study area

It can be seen from Fig 4.10 and Fig 4.11 that, the water quality at the outlet of the park is much better than that at the entrance, and the wetland has a remarkable ability to degrade pollutants. According to the calculation, the degradation of nitrogen and phosphorus in LinGang Eco-Wetland Park in 2017 were 5764.38kg and 2070.79kg, respectively.

Based on the different ecological protection levels, the LinGang Eco-Wetland Park is divided into three parts: development prohibited area, development restricted area and development recommended area. In the range of development recommended area, as the analysis have shown that the wetland has a remarkable ability to degrade pollutants from the outlet to the entrance and considering the traffic accessibility. Figure 4.12 shows the final location of the ecological expo architecture on LinGang wetland park.

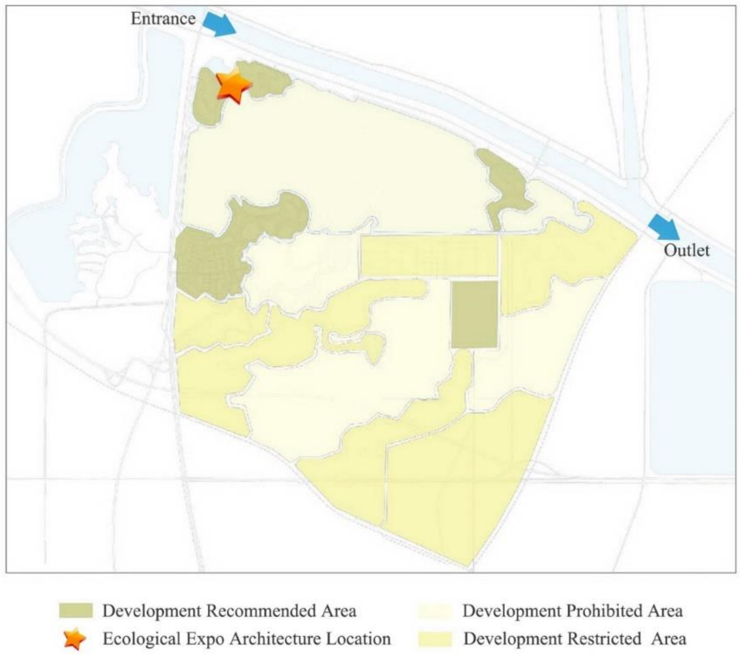

Figure 4.12 Final location of the ecological expo architecture on LinGang wetland park

4.4 Illustration of Case Study 1

Case study 1 examines the first level of CTO in architecture linked with ecosystems as the environment. In this case, we firstly abstract and review 'location' into four sub-concepts: regional network, building scale, traffic accessibility and environmental. Among these four sub-concepts, regional network, building scale, traffic accessibility are well-defined concepts, thus it's easy to define and fulfil. However, environmental is an ill-defined concept thus we acknowledge the expo-building as a CAS and link it with local ecosystems in the LinGang wetland park as the environment. Then CTO design approach inspires us to analyze the water which is the interaction between building and local ecosystem and finally design the environmental location. After the exercise, we sought for feedback from the designers regarding their experiences of using CTO as a rapid ideation aid. All of them agreed that CTO design approach stimulated them to find clear and effective methods to deal with complex and ill-defined problems in architecture design.

Chapter 5 Case Study2: A New Method for Human-Centered Architecture Space Design Based on Substance-Field Analysis

This chapter is from the following conference paper:

Shen, T., Nagai, Y., & Kim, E. (2019). A New Method for Architecture Space Design Based on Substance-Field Analysis. In *IOP Conference Series: Earth and Environmental Science* (Vol. 233, No. 2, p. 022027). IOP Publishing.

Research about novel methods in the architectural design process can enlarge design researches. Structured design methods can make the design process more organized and learnable, thus we use Substance-Field (Su-field) as the ground structure in this case study. Analysis Substance-Field (Su-field) Analysis is a TRIZ analytical tool for modeling problems related to existing technological systems. Meanwhile, the space concept is vital in architecture. This chapter aims to present a new method for more creative human-centered architecture space design based on substance-field analysis through CTO design thinking approach. Figure 5.1 shows the model of CTO in case study 2. In this method, human is the design agent, 'Field' for human is the environment and Su-field model is the ground structure. A controlled experiment demonstrates the effectiveness of this method by measuring idea quality and quantity.

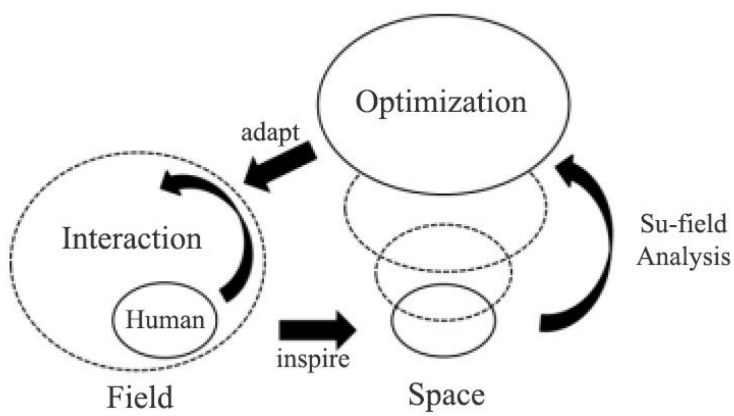

Figure 5.1 Model of CTO in case study 2

5.1 Introduction

TRIZ (theory of inventive problem-solving method) is a systematic approach which successfully reveals the inherent laws and principles of creating inventions. Focusing on clarifying and emphasizing the contradictions existing in the system, its goal is to completely resolve the contradictions and obtain the final ideal solution (Savransky, 2000). The major tools and methods of TRIZ include '40inventive principles', 'Su-field Analysis', '76 General solutions' and 'evolution analysis'.

Many applications of TRIZ theory in architecture has been presented. Mann & Catháin (2005) explained the TRIZ theory to train students in architecture design education. Padmanabhan (Padmanabhan, 2013) affirmed and solved the problem of increasing wind power in buildings using TRIZ Tool in cities by an experimental method. Ruey-Sen (Chiu & Cheng, 2012) explored TRIZ application for the improvement of heat insulation for roof steel plates. Kankey (2005) also discussed improving the acoustics in a historic building using TRIZ. However, these researches primarily focus on applying TRIZ theory in construction technology field, the difficulties of applying TRIZ theory in architecture design process are due to architecture's attributes, Rittel (1998) and Cross (1994) characterized it as wicked problems. More specific, the architecture design process is based on fuzzy or ambiguous information, with undefined problem requirements and conflicting parameters as well as a lack of general solution methods (Kiatake & Petreche, 2012). As a result, these attributes explain the complexity inherent in the architecture design process, the decomposition of which into the building and solving problems has reached wider research fields, including cognitive psychology.

Herein, a new method and general solutions for more effective architecture space design based on Su-field Analysis model are presented to demonstrate the potential of TRIZ theory in architecture design process. In addition, a controlled experiment demonstrates the effectiveness of this method by measuring idea quality and quantity.

5.2 Related Works & The New Method for Architecture Space Design

Traditional method in architecture space design includes the following four steps (Ching,2014):

Step 1: Collect numerous requirements from the client and user.

Step 2: Build the brief to response to the requirements in step 1.

Step 3: Consider spatial relationships.

Step 4: Create the solution.

The traditional architecture space design method is a linear problem-solving design process (British Design Council, 2015). However, Innovation should not be seen as a linear process, it should be a feedback loop — 'Build, Measure, Learn' — (Ries, 2011) focused on swiftly improving the existing solution. In addition, this case study link human with architecture as a changing environment, thus the new method for architecture space design is a human-centred design method, in which the key principle is that designers 'empathize with the end user' (Kelley and Kelley, 2013).

In TRIZ theory, Su-field Analysis is an analytical tool for modelling problems related to existing technological systems. The desired function is the output from an object or substance (S1), caused by another object (S2) with the help of some means (Technical Fields, F) (Terninko et al.,1998; Terninko, 2000: Mao & Zhang, 2007). Figure 5.2 shows the basic model of Su-field Analysis.

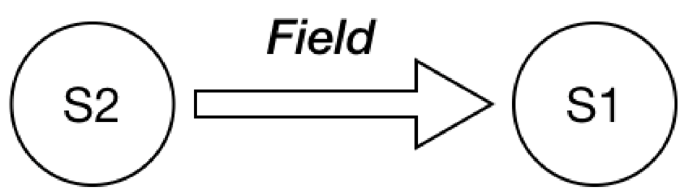

Figure 5.2 The basic model of Su-field Analysis

Belski (2008) summarized the technical fields as 'MATCEMIB' shown in Table 5.1.

Table 5.1 Technical fields in Su-field Analysis

Fields	Interactions Including
Mechanical	Gravitation, collisions, friction, direct contact
	Vibration, resonance, shocks, waves
	Gas/Fluid dynamics, wind, compression, vacuum
	Mechanical treatment and processing
	Deformation, mixing, additives, explosion
Acoustic	Sound, ultrasound, infrasound, cavitation
Thermal	Heating, cooling, insulation, thermal expansion
	Phase/state change, endo-ex-thermic reactions
	Fire, burning, heat radiation, convection
Chemical	Reactions, reactants, elements, compounds
	Catalysts, inhibitors, indicators (pH)
	Dissolving, crystallisation, polymerisation
	Odour, taste, change in colour, pH, etc.
Electric	Electrostatic charges, conductors, insulators
	Electric field, electric current
	Superconductivity, electrolysis, piezo-electrics
	Ionisation, electrical discharge, sparks
Magnetic	Magnetic field, forces and particles, induction
	Electromagnetic waves (X-ray, Microwaves, etc.)
	Optics, vision, colour/translucence change, image
Intermolecular	Subatomic particles, capillary, pores
	Nuclear reactions, radiation, fusion, emission, laser
	Intermolecular interaction, surface effects, evaporation
Biological	Microbes, bacteria, living organisms
	Plants, fungi, cells, enzymes

5.2.1 Human-field (Hu-field) Analysis

For architecture space design, we define S1 is human and S2 is the spatial element. Hence, we present the original proposition – Human-field Analysis as the new method for human-centred architecture space design.

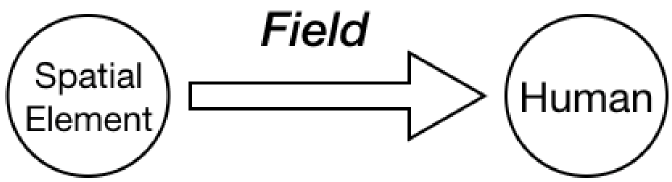

Figure 5.3 The basic model of Hu-field Analysis

There are four basic principles included in Hu-field Analysis:

1. Effective complete architecture space system contains human, spatial elements and field.

2. Incomplete architecture space system requires completion or a new space system.

3. Ineffective complete architecture space system requires improvement to create the desired space.

4. Negative complete architecture space system requires the elimination of the negative effect.

In Hu-field Analysis, we also summary the factors of fields in architecture space design targeted at human.

Table 5.2 Human fields in architecture space design

Field Essence	Interaction	Contents
Physics Senses	Vision	colour, shape, movement
	Sound	loud, quiet
	Touch	smooth, rough
	Heat	hot, pleasant, cold
	Balance	normal, abnormal
Psychology	Time	continuity, order

Perception	Optical	size, weight, time, movement,
	Orientation	direction, location
	Sensory	hallucination, imagination

5.2.2 Making a Model

The effect of architecture space could be on human from the output of the field information. The term field is used in the broadest sense, including the fields of physics and psychology. A complete architecture space model is a triad of human, spatial elements and the field.

The innovative problem is modelled to show the relationships among spatial elements, human and the field. Complex systems can be modelled by multiple, connected Hu-field Models.

There are four steps to follow in making the Hu-field Model:

1. Identify the spatial elements. Spatial elements comprise architecture space which is either acting upon human or is within substance 2 as a system.

2. Construct the model. After completing these two steps, stop to assess the completeness and effectiveness of the system. If some element is missing, try to identify what it is or find the substitute.

3. Consider design solutions from the General Solutions.

4. Develop a concept to support the solution. In following Steps 3 and 4, activity shifts to other knowledge-based tools.

5.2.3 Analysis Nomenclature

In Hu-field Analysis model, the human is the recipient of the system action. Spatial elements are the means by which field can be achieved. We abstract spatial element as:

(Po) — Point

(Li) — Line

(Su) —Surface

There are six different connecting relationships between the spatial element and human expressed by different symbols and shown in Figure 5.4.

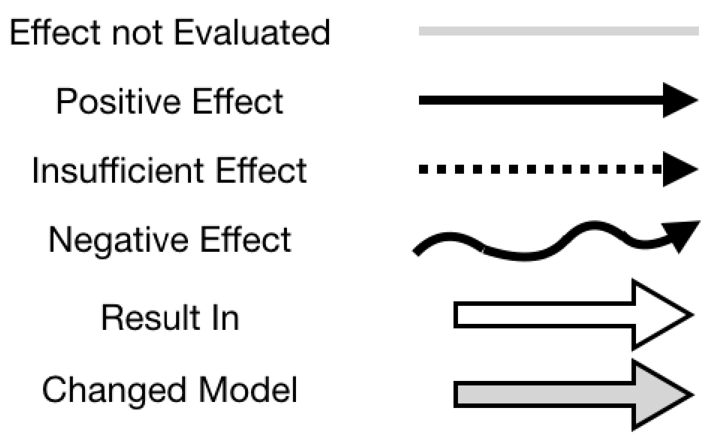

Figure 5.4 Six relationships between the spatial element and human

5.2.4 General Solutions

There are 5 general solutions in Hu-field Analysis based on the 7 general solutions in Su-field Analysis.

- General Solution 1: Complete an Incomplete Hu-Field Model

Complete a Hu-field model if any of its three components is missing.

- General Solution 2: Modify Spatial Elements to Eliminate or Reduce Negative Impact

Designers can change internally or externally and temporarily or permanently the characteristics of spatial elements to eliminate or reduce the negative impact on the human in architecture space.

- General Solution 3: Change Existing Field to Reduce or Eliminate Negative Impact

Reconsider or change the existing field in Hu-field model to reduce or eliminate negative Impact.

- General Solution 4: Eliminate, Neutralize or Isolate Negative Impact by Introducing a Positive Field

When the current architecture space has the negative impact on human, designers can introduce a positive field to increase the positive effect and reduce the negative effect of architecture space. For example, when the architecture space is too narrow, which belongs to the ‘scale field', ‘color field' can be introduced where light and cool color can make space large and bright.

- General Solution 5: Expand Existing Hu-Field Model to a Chain

Expand the existing Hu-field model to a chain by introducing a new Sub-Hu-field model to the system.

5.3 Data Collection and Analysis

In this study, we use a control experiment demonstrates the effectiveness of this method by measuring idea quality and quantity.

5.3.1 Participants

In this experiment, participants consisted of 16 students pursuing the bachelor of architecture in the same university, they all completed the basic architecture course and got the credits.

5.3.2 Analysis of Idea Quality

In this study, we adopt the method presented by Shah, Smith, and Vargas-Hernandez (2003). In this method, idea quality can be sufficiently estimated even though there is not enough quantitative information to do formal analysis at the concept stage. In addition, this method adds all the quality scores for all the alternatives to achieve the total score for the set. As a result, the idea quality is defined as:

$$\boldsymbol{M} = \sum_{j=1}^{m} \boldsymbol{f_j} \sum_{k=1}^{2} \boldsymbol{S_{jk} p_k} \Big/ \boldsymbol{n} * \sum_{j=1}^{m} \boldsymbol{f_j}$$

In this equation, S_{jk} is the score for quality for function j at stage k; m is the total number of functions; fj is the weight for function j; p_k is the weight for stage k. The denominator is for normalizing to a scale of 10.

5.3.3 Experiment Process

The 16 participants were divided into Group A and Group B, they were all asked to design play space for children under 12 years old in an hour. The difference is that Group A were trained and used Hu-field Analysis in the whole design process, whereas Group B completed the design task using traditional method.

5.3.4 Experiment Results

Finally, we got all the design ideas from the 16 participants and Table 5.3 shows the idea of quality and evaluated them by measuring their quality and quantity. Table 5.3 shows the idea quality and quantity of each participant.

Table 5.3 Idea quality and quantity of each participant

Group A	Idea Quality	Idea Quantity	Group B	Idea Quality	Idea Quantity
A1	6.15	3	**B1**	4.14	2
A2	5.64	2	**B2**	3.56	3
A3	4.96	4	**B3**	4.07	2
A4	6.54	3	**B4**	4.21	1
A5	5.46	4	**B5**	5.13	3
A6	4.87	3	**B6**	3.76	2
A7	5.12	6	**B7**	4.28	2
A8	5.98	4	**B8**	5.76	3

Then we analyzed these data with Unpaired Samples T-test, Table 5.4 shows the result.

Table 5.4 The result of the Unpaired Sample T-test

Group	Idea Quality $\overline{X}$	Idea Quality SD	Sig	Idea Quantity $\overline{X}$	Idea Quantity SD	Sig
A	5.59	0.60	0.04	3.63	1.19	0.028
B	4.36	0.73	<0.05	2.25	0.71	<0.05

Both the results of idea quality and idea quantity are significant, it can indicate that Hu-field Analysis is an effective tool in architecture space design as it has the ability to promote both participants' idea quality and idea quantity.

5.4 Discussion

Su-field Analysis is an analytical tool in TRIZ which related to solving technological problems. In this study, we deconstruct Su-field Analysis and present Hu-field Analysis, however, the human is a more complex system relative to technique system. Therefore, when applying the Hu-field Analysis, it is crucial for designers to analyse and understand the needs of human.

Hu-field Analysis can also be expanded to other human-centred design fields such as environmental design, interaction design, clothes design and service design. Taken together, Hu-field Analysis requires the deep understandings of human and it may prepare designers for capturing core values in the broad field of design.

5.5 Summary

In this chapter, we present Hu-field Analysis for architecture space design and conduct a control experiment to demonstrates the effectiveness of this method by measuring idea quality and quantity. However, ideation effectiveness also includes idea novelty and idea variety, as well as Hu-field Analysis in architecture space design, needs to be explored potentially by conducting more human experiments and considering more design contexts.

5.6 Illustration of Case Study 2

Case study 2 examines the second level of CTO in architecture linked with human as the environment. In this case, we firstly introduce the traditional architecture space design method which is a linear problem-solving design process, then we present the new method which is human-centered and builds a non-linear innovative feedback loop. Human is a typical CAS, case study 2 demonstrates that CTO has the ability of linking architecture with other related CASs making up an ecosystem so that to achieve the goal of co-evolution.

Chapter 6 Case Study3: Design of Building Construction Safety Prediction Model Based on Optimized BP Neural Network Algorithm

This chapter is from the following journal paper:

Shen, T., Nagai, Y., & Gao, C. (2019). Design of building construction safety prediction model based on optimized BP neural network algorithm. *Soft Computing*, doi: https://doi.org/10.1007/s00500-019-03917-4

In order to solve the safety problem of the construction industry, the construction safety prediction model based on the optimized Back Propagation (BP) neural network algorithm is designed in this study. The back propagation (BP) neural network algorithm is a multi-layer feedforward network trained according to error back propagation algorithm and is one of the most widely applied neural network models. BP network can be used to learn and store a great deal of mapping relations of input-output model, and no need to disclose in advance the mathematical equation that describes these mapping relations. Its learning rule is to adopt the steepest descent method in which the back propagation is used to regulate the weight value and threshold value of the network to achieve the minimum error sum of square (Li et al., 2012). Firstly, the characteristics of the construction industry were analyzed. As a labor-intensive industry, the construction industry is characterized by numerous factors such as large investment, long construction period and complicated construction environment. Due to the increasingly serious security problem, widespread concern over such problem has been aroused in society. As a result, we argue the optimal 'safety' in building construction is the emergence of 'safety prediction'. Secondly, the problem of building construction safety management was summarized, six influencing factors were explored and a building construction safety prediction model based on rough set-genetic-BP neural network was established. Finally, the model was validated by a combination of multiparty consultation, empirical analysis and model comparison. The results showed that the model accurately predicted the risk factors during the construction process and effectively reduced casualties. Therefore, the model is feasible, effective and accurate. In this method, worker is the design agent, construction environment is the environment and BP neural network algorithm is the ground structure. Figure 6.1 shows the model of CTO in case study 3.

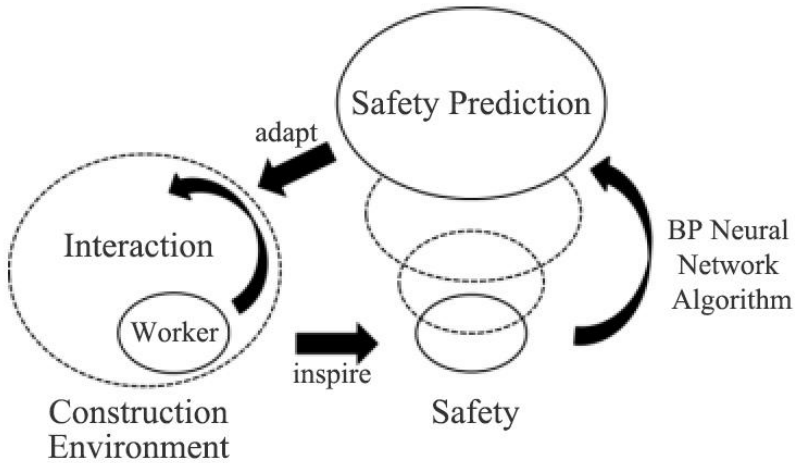

Figure 6.1 Model of CTO in case study 3

6.1 Introduction

Safety prediction management of building construction was studied. According to the risk factors in the construction project, a security prediction model based on RS(Rough Set)- GA (Genetic Algorithm) BP (Back Propagation) algorithm is established to turn the current passive follow-up safety management mode into active one before the safety management mode is inspected, which provides targeted preventive measures for safety production in the next step. This has certain warning and reference function to the construction safety management. Besides, the traditional management of the construction industry has been changed.

The construction industry is one of the pillar industries of China's national economy. The annual total investment in capital construction accounts for about 13% of the gross national product (Wang et al. 2015). Moreover, the stable development of the construction industry plays an important role in the healthy development of the national economy and the improvement of people's material and cultural life. The construction industry is a labor-intensive industry characterized by numerous influencing factors such as large investment, long construction period and complex construction environment. These characteristics determine that it is an accident-prone and high-risk industry. Every year, thousands of employees die from work, resulting in direct economic losses of more than 10 billion. As a developing country, China's construction industry has a more intensive labor force than that of developed countries. The technical level is relatively low; the number of construction safety accidents and the number of deaths per year are significantly higher than those of developed countries. The frequent construction safety accidents in China has not only seriously hindered the development of the construction industry, but also brought huge property losses to the society, seriously affecting the healthy development of China's national economy. Under the market economy, the increasingly prominent security issues have aroused widespread concern in the whole society. In particular, in recent years, security issues have been highly valued. A large amount of manpower, material resources and financial resources have been invested to improve the safety production level of construction pro- jects, a series of policies and regulations on safety have been introduced and the domestic project management security system has been improved and strengthened. At the same time, some scholars have begun to study the theory of building construction safety management systems. For example, Fang Dongping of Tsinghua University conducted an in-depth study on the relationship between safety investment and safety performance of construction projects (Yu et al. 2015). Wang Jizhi and Hua Yan of Tsinghua University put forward the importance and specific recommendations of safety standardization management (Meng et al. 2016). Guan Ke et al. conducted a useful discussion on the method of building construction safety evaluation (Gordan et al. 2016). Some researchers have made some suggestions on the nature of security. Unfortunately, although the laws and regulations and management theory are constantly improving, it is unsatisfactory in realizing the safe production of construction projects. The phenomenon of frequent construction safety accidents has not been fundamentally reversed. In the event of tens of billions of dollars in accident losses, the safe production issue is still very serious. This system and the similar measures cannot effectively curb the highly frequent construction safety accidents. It is thus necessary to profoundly think about the current building safety management system. While implementing relevant laws and regulations, the researcher has to examine and change the status quo of building safety management from a new perspective. Security management of the pre-control mode is applied. Combined with multidisciplinary solutions, security prediction theory, data mining technology, modern artificial intelligence technology and computer software information technology were applied. A building construction safety prediction model based on rough set-genetic-BP neural network was established. The feasibility, effectiveness and accuracy of the model were proved by the combination of multiparty consultation, empirical analysis and model comparison. The model was used in safety production practices. Finally, the pre-control measures for construction engineering safety accidents were studied.

Based on the above background conditions, the construction safety prediction was studied. The risk factors for the safe production of construction projects were fully recognized. A predictive model of building construction safety was established. The aim is to transform the current post-event and passive security management models into active pre-adjusted management models. This plays a certain role in warning and guiding the safety management of building construction. Fundamentally, this passive construction safety management situation has been changed.

6.2 State of the Art

6.2.1 Research Status of Foreign Security Forecasting

In all industry developments, the average rate of accidents in construction projects far exceeds that in most other industries. Studies have shown that even in the UK with a high level of safety management, the economic losses caused by construction safety accidents are as high as 3–6% of the total project cost; the economic losses caused by construction safety accidents in the USA even reach 8–14% of the total project cost. How to better protect the safety of building construction and reduce the incidence of accidents is the focus of attention of all countries. There is an urgent need to solve this problem in the field of engineering and construction (Liu et al. 2015).

Early warning was first applied to the military field. With the needs of construction and development, it has gradually developed into nature, economic construction and other fields. The related ideas of early warning theory originated from theories of crisis management and risk management. The early warning management theory is mainly used for macroeconomic monitoring and early warning. Therefore, this is widely used in the macroscopic field. With its promotion and application in the macroeconomic field, early warning has also begun to be applied in the microscopic field, such as weather warning and corporate financial early warning (Hajihassani et al. 2015a). In the 1970s, Japanese researchers applied early warning to environmental pollution and earthquake disasters. In the mid-1980s, American scholars extended early warning research to corporate management, which was mainly to study the emergency measures adopted by enterprises in the face of crisis. In the late 1990s, early warning research in the UK, Japan, Russia, the USA and other countries had been further developed. Some scholars proposed an early warning model for using the cash flow information to warn the financial distress of enterprises, and some scholars began to study the early warning system of SMEs. Risk warnings have gradually gained attention in the academic and practical fields and have been tried and promoted in various industries (Bui et al. 2016).

In the earlier period, the main direction of the study of early warning in the USA and Japan was to respond to the response measures after an incident occurred. Compared with Japan and the USA, China's research on early warning is lagging behind, and the research direction is mainly focused on how to apply early warning to economic issues. At the international level, research on early warning issues in the USA and Japan started earlier. As early as the mid- 1980s, the USA had been engaged in early warning research on corporate crisis management and strategy. In the late 1980s and early 1990s, Japan also began to study the issue of corporate crisis management early warning. The main research directions of the USA and Japan focus on how to respond to emergency measures and counter- measures after the crisis. However, there is no mechanism analysis and empirical research on the cause of the crisis.

The Louisiana State University scholars Mengqiu Ye et al. analyzed the variation of five vehicle driving parameters (speed, longitudinal acceleration, lateral acceleration, yaw rate and throttle position). Three subtasks (call, text and conversation) were chosen to build the model. The model used a supervised feedforward artificial neural network (ANN) structure to describe the effects of inherent nonlinearities between driving behavior and secondary tasks. The results showed that the selected driving performance indicators could effectively detect the related secondary mission operations. The impact of cognitive driving subtasks on driving performance and visual search behavior was discussed. The results showed that the correct response rate under dual-task conditions (main driving and cognitive tasks) was significantly lower than that in the main driving task. In addition, novice drivers performed worse on cognitive tasks than experienced drivers. Studies have shown that both mobile phone calls (cognitive distraction) and text messages (which have both cognitive and visual distractions) increase the response time of drivers to pedestrian conflicts, and the messaging is more serious (Hu et al. 2017).

6.2.2 Research Status of Chinese Domestic Safety Forecast

From the late 1980s to the end of the 1990s, China's early warning management research began to develop. Since the 1980s, research on early warning has undergone tremendous development and transformation. The main manifestation is that the macroeconomic early warning gradually turns to the enterprise early warning, and the early warning gradually turns to the state early warning and the qualitative early warning is transformed into the quantitative and qualitative early warning research. The study on China's early warning management is carried out from the macroeconomic point of view, and theoretical research becomes mature, such as the research on early warning techniques and methods of neural networks. The research on early warning theory has gradually extended to various fields, such as coal mine safety warning, financial risk warning, industrial investment warning, construction safety warning, technical early warning, aviation industry early warning and unemployment risk warning.

From the end of the 1980s, China gradually carried out research on enterprise early warning management. In 1989, the concept of enterprise adversity management was pro- posed. The early warning management theory analyzed the causes and history of security incidents. To achieve safety standards, safety precautions were used to improve the level of safety management of controls and warnings. Other researchers have also explored other areas of early warning management. Early warning management used a new perspective to manage security. This new management method analyzed the development of events using positive and negative angles and grasped the causes and principles of development in the negative direction. On this basis, the corresponding program plan is formulated, and then some means are used to ensure the development in the positive direction.

Real-time road traffic data are collected. By analyzing vehicle driving data and road scene information, this study establishes several task distraction prediction models. The results of the study indicate that when the subtask is highly distracted, the use of car radios and CD players should be warned or prohibited to reduce the interference of the distracted subtasks on the driver. Li Yang (2015) of Jilin University conducted an analysis of the safety evaluation index of multi-attribute driving behaviors for the driver's basic information, visual perception, decision response and psychological endurance, vehicle control and driving status. And, the driving behavior safety evaluation model was established by TOPSIS method (Hajihassani et al. 2015b).

6.2.3 Rough Set Theory

The rough set theory was proposed by the Polish mathematician Z. Pawlak in 1982 when the data were analyzed. Its main purpose is to analyze a series of complex data. System data are classified by attributes. The rough set is used for reduction according to the importance of the inter- material quality change, and the decision is known by the reduction result. Rough set theory mainly includes the construction of decision tables, the definition of equivalence relations, the calculation of approximate sets, the reduction in attributes and the screening of decision attributes (Yi et al. 2016). Attribute reduction between indicators is the core module in rough set theory. The importance of each element in the data system is determined by the attributes of the element. There may be more than one data for the same attribute, which may result in data redundancy. Indicators were collected for social responsibility in the specific implementation process of construction enterprise projects. In this process, the greater the proportion, the higher the probability of data redundancy. In turn, the impact on corporate project-level CSR strategy selection is likely to be greater. In the process of screening the project-level CSR strategy of the construction enterprise, the interests of the stakeholders of the project are mostly presented through qualitative indicators. In the process of reducing relevant qualitative indicators, rough set theory can screen out the most fundamental interests of construction enterprise project stakeholders under the premise of avoiding the influence of subjective empowerment on project-level CSR strategy screening (Saghatforoush et al. 2016). Therefore, in the case of ensuring that the selected project-level Corporate Social Responsibility (CSR) strategy of the construction enterprise is scientific and reasonable, the same condition attributes of each stakeholder of the project are reduced. Redundant attributes were removed to reduce the amount of data processed during the CSR strategy screening process for construction companies. This helps to fundamentally excavate the most fundamental interests of the stakeholders in the construction enterprise project during the project. On this basis, the interests of stakeholders are met, and the project goes smoothly.

6.3 Methodology

6.3.1 Risk Reduction in Building Construction Based on Rough Set-Rosetta

In rough set theory, knowledge is seen as a division of the domain U, which is an ability to classify objects. 1U$\neq\emptyset$ is a finite set of given research objects, which is a discourse domain. The classification is associated with knowledge and the equivalence relation R is used to represent the classification. Knowledge is understood as the division of the equivalence relation R to the domain U.

An indistinguishable relationship, also known as an equivalence relation, divides U into a finite set called an equivalence class. In each equivalence set, objects are indistinguishable. If P⊆R, and P$\neq\emptyset$, it is denoted as IND(P):

$$IND(P) = \{(x, y) \in U \times U, \forall a \in P, f(x, a) = f(y, a)\} \tag{1}$$

For $\forall x \in U$, its P equivalence class is defined as:

$$[x]_p = \{y \in U | (x, y) \in IND(P)\} \tag{2}$$

If $X \subseteq U$, R is an equivalence relation on U. A definable set is called an R-accurate set; otherwise, X is called R-undefinable, and an undefined set is called an R-rough set. A rough set can be described by two exact sets, namely the upper approximation and the lower approximation of the rough set.

The smallest definable set contained in X is called the upper approximation of X:

$$\overline{R}(X) = \{x \in U | [x]_R \cap X \neq \varphi\} \tag{3}$$

The largest definable set contained in X is called the R lower approximation of X:

$$\underline{R}(X) = \{x \in U | [x]_R \subseteq X\} \tag{4}$$

The basics of rough set theory are studied. Flowchart of attribute reduction based on rough set theory is as shown in Figure 6.1.

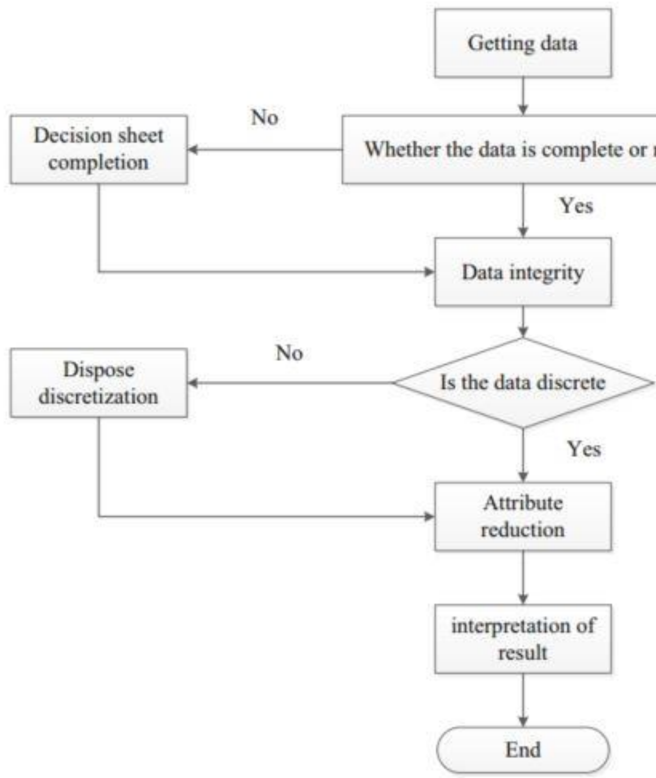

Figure 6.1 Flowchart of attribute reduction based on rough set theory

At present, remarkable international achievements have been made in the research and development of rough set application software. For example, Kansas University in the USA developed a rough set-based instance learning system LERS, and Regina University of Canada developed database knowledge discovery KDD2R software based on the Variable Precision Rough Set (VPRS). The rough set data mining is ROSETTA software based on the RS theory of the tabular data analysis toolkit developed by the Department of Computer and Information Science of the Norwegian University of Science and Technology and the Institute of Mathematics of the University of Warsaw, Poland.

In addition to providing a graphical interface, ROSETTA software also provides the following functions:

The input/output obtains the data source through ODBC and DBM, and the information table can also be obtained through the software-defined text format.

Preprocessing supports decision table completion, decision table discretization, and so on.

The calculation can effectively reduce the different types of indistinguishable relationships and obtain the if–then rule or the description mode represented by the reduced form.

Subsequent processing can filter out non-conforming reduction results and decision rules.

The resulting rules are validated and analyzed. Attribute reduction is the core content of rough set theory (Liou et al. 2016). The ROSETTA software combined with genetic algorithm is used to reduce the conditional attributes of the sample.

Building safety issues are a nonlinear and complex problem. Considering the finiteness of the sample data, the most conducive reduction results are adopted, i.e., $\{a_1, a_2, a_3, a_6, a_8, a_{10}\}$ are the risk factors for the final prediction model (Waziri et al. 2017; Chatterjee et al. 2017). They represent the workload of high places, the degree of perfection of safety protection, the situation of the construction site, the safety of untrained workers, organizational command capabilities and safety materials. From the actual situation of construction safety accidents, safety incidents caused by these six factors often appear. The characteristics of construction safety production and the types of multiple safety accidents were studied. On the basis of ‘‘4M,’’ a risk factor system was established. Therefore, each of these six factors plays an important role and they are representative. For actual projects, the collection of various factor data is relatively easy and objective, and it is no longer possible to reduce it (Ye et al. 2018; Gholizadeh 2015; Kuang et al. 2017). This fully reflects the powerful knowledge mining ability of the rough set, and the most important influencing factors can be found. The reduction results are objective and reasonable. Therefore, the last set of reductions is selected as a set of attributes for building construction safety prediction.

Data mining technology was introduced into the field of building construction safety prediction. The current leading-edge data mining method, rough set method, was used to reduce the risk factors for construction safety production. Combined with the sample data, six main factors affecting the safety of building construction were obtained. Rough set theory was applied. With the help of ROSETTA software, attribute reduction results were obtained. It was relatively simple and easy to understand this process (Leu and Liu 2016). Besides, the factors affecting redundancy were removed. The reduction results were the core factors affecting the safety of building construction, and they provided a good support for the establishment of building construction safety prediction models. Key factors were predicted. As a result, the timeliness and accuracy of security forecasts are greatly improved. At the same time, the practicality of building construction safety prediction is enhanced.

6.3.2 Building Construction Safety Prediction Model Based on RS-GA-BP

BP network structure design Before using the genetic algorithm to optimize the weights and thresholds of BP neural networks, the basic structure of BP networks was first designed. The determination of BP network structure mainly included the number of input layer nodes, the number of output layer nodes, the number of hidden layer nodes (the number of neurons) and the transfer function between layers (Liu et al. 2016).

According to the results of the reduction, the six indicators of people's high workload, safety protection, construction site, untrained workers, organizational command capability, and safety materials were selected as the final input parameters. Therefore, the number of input layer nodes in the network structure is 6 (Zhang et al. 2017). The number of output layer neurons in the BP network is consistent with the expected output. The decision variable of the sample is a thousand-person injury rate, which is directly represented by a number, so the number of output layer nodes is 1.

A BP network can contain a different number of hidden layers. However, it has been theoretically proved that a BP network with only one hidden layer can achieve arbitrary nonlinear mapping and is the most widely used (Roy et al. 2016; Kusi-Sarpong et al. 2015). As a result, the number of hidden layers in the model is 1. The BP network structure has three layers: The first layer is the input layer, the second layer is the hidden layer and the third layer is the output layer. The network structure is shown in Figure 6.2.

The number of hidden layer nodes is determined below. The selection of the number of hidden layer nodes has a great influence on the performance of the neural network. At present, it is commonly used to find the number of nodes of the hidden layer by the following three empirical equations. The number of final hidden layers is determined using a trial-and-error method.

$$S_1 = \sqrt{S_0 + S_2} + \alpha \tag{5}$$

$$S_1 = \sqrt{S_0 \times S_2} \tag{6}$$

$$S_1 = 2S_0 + 1 \tag{7}$$

In the equation, S1 is the number of hidden layer nodes, S0 is the number of input nodes and S2 is the number of output nodes. a is an adjustment constant between 1 and10. According to the above three empirical equations, the number S1 of hidden layer nodes is obtained separately (Jia et al. 2016). Then, by changing S1, the neural network (MATLAB program) is used to determine the number of hidden layer nodes corresponding to the minimum network error. The log-sigmoid type function is chosen as the transfer function of the network to test the network errors of different hidden layer nodes.

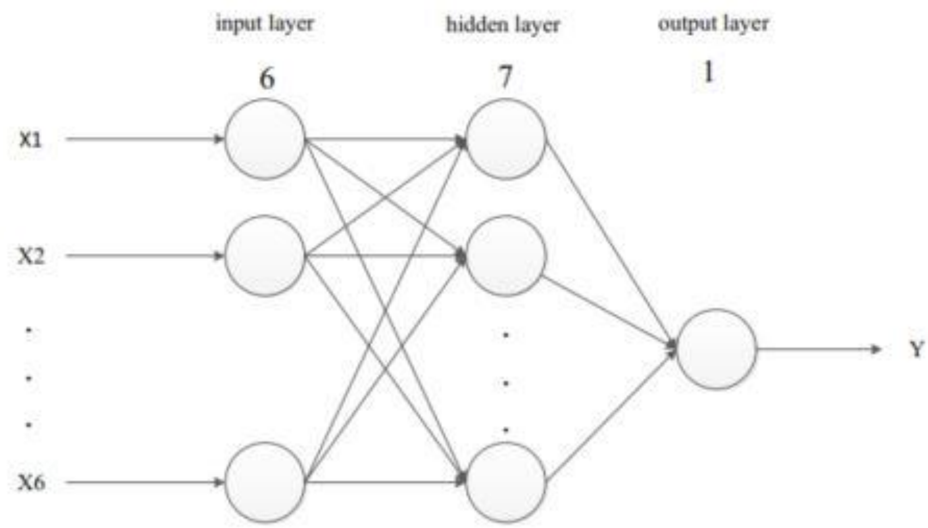

Figure 6.2 Structure diagram of BP neural network

The training results are shown in Table 6.1.

Table 6.1 Network training error

Hidden layer node	8	9	10	11	12	13
Network error	0.1667	0.1642	0.1362	0.1547	0.1402	0.1187
Step number	13	17	14	14	15	10

As can be seen from Table 1, under the condition that the number of training steps is 100 and the target network error is 0.001, the number of hidden layer nodes is 13, and the BP network has the best approximation effect on the function. Its error is minimal, and the network has reached the target error after training 10 times.

Due to some excellent characteristics, genetic algorithm has been widely used in many aspects and achieved good results. The operation process of the genetic algorithm is shown in Figure 6.3. The specific steps are described as follows:

Step 1 Parameter initialization. The size of the population and the genetic algebra were determined. The way the chromosomes are encoded is selected and encoded.

Step 2 Determination and calculation of the fitness function.

Step 3 Select operation.

Step 4 Crossover operation.

Step 5 Mutation operation.

Step 6 Termination of conditional judgment. The maximum genetic algebra is judged. If the maximum genetic algebra is reached, the most adaptive function is the final optimal result (Chen and Tsai 2016). If there is no maximum genetic algebra, Step 2 is performed and the above process is repeated.

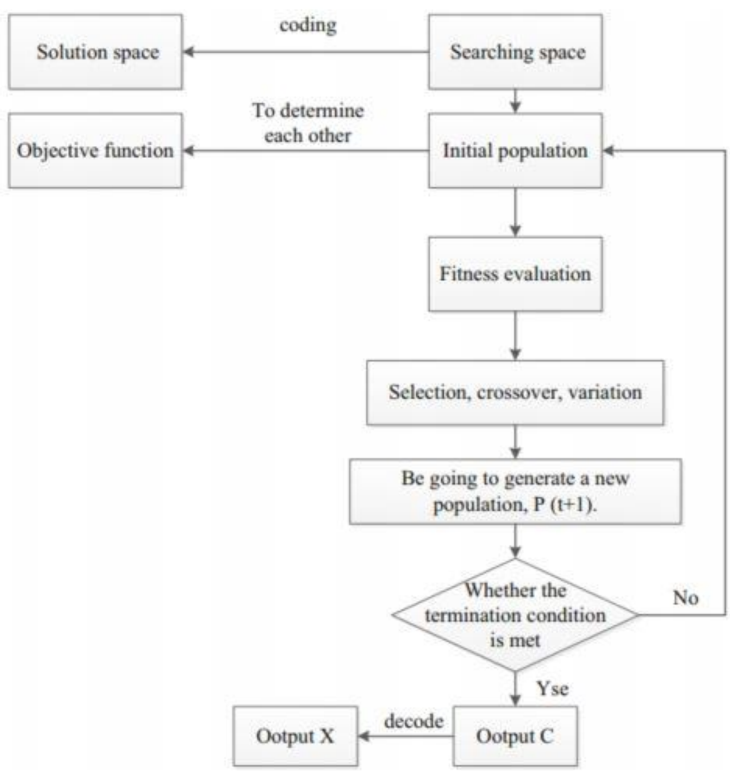

Figure 6.3 The operation process of the genetic algorithm

BP network optimized by genetic algorithm: After determining the structure of the BP neural network and before training on the network, genetic algorithms are needed to optimize the weights and thresholds of the BP network. The optimal initial weights and thresholds are found and assigned to the BP network. It is trained in BP algorithms. The relevant explanations for genetic algorithm optimization initial weights are as follows:

First, chromosome coding and initial population formation. The coding methods of the GA algorithm mainly include binary coding, gray code coding and floating-point coding. Floating point coding is adopted, which can reduce the coding length and improve the accuracy and efficiency of the algorithm. The code length is:

$$S = S_0 \times S_1 + S_1 \times S_2 + S_1 + S_2 \tag{8}$$

Second, the objective function and the fitness function. The role of the genetic algorithm is to search the weights and thresholds of the network to minimize the error function E(ζ) in the BP network. That is, minE(ζ) is the objective function of the genetic algorithm. In the evolution of genetic algorithms, the evaluation of chromosomes is done by the fitness function and evolves toward the increase of the fitness value. Therefore, the fitness function and the objective function need to be transformed accordingly, and the fitness function is defined as:

$$F(\zeta)=1/\mathrm{E}(\zeta) \tag{9}$$

Finally, the roulette selection method is used to perform the selection operation. Commonly used crossover probabilities range from 0.2 to 0.5. The probability of variation is between 0.001 and 0.1. Crossover and mutation operations are performed using the default crossover and mutation rates in the genetic algorithm toolbox. Table 6.2 lists the basic control elements of the genetic algorithm and related information.

Table 6.2 Genetic algorithm basic control elements and information

Pop size	100
Maxgen	100
Encoding length(S)	105
System of selection	Roulette selection
Crossover probability(P_c)	Toolbox default
Mutation probability(P_m)	Toolbox default

After determining the above parameters, the weights and thresholds of the BP neural network were optimized using the genetic toolbox (gaot) on the MATLABR2009a platform.

BP network training During the training of the BP neural network, data of 36 samples were analyzed. In the 36 samples, 32 samples 1–4, 6–13, 15–21, 23–26 and 28–36 were selected as training samples for BP neural networks to train the network. The four samples 5, 14, 22 and 27 were used as test samples to test the effect of network prediction.

The 91 weights and 14 thresholds obtained by genetic algorithm optimization were assigned to the BP neural network.

In order to verify the accuracy and validity of RS-GA- BP forecasting model, the relevant content of model comparison is added to make a comparative analysis of RS- BP forecasting model without genetic algorithm optimization. The accuracy and validity of RS-GA-BP forecasting model are further tested and validated according to the forecasting value of training samples and testing samples.

In order to establish a comparative relationship with RS- GA-BP prediction model, the same network structure of the two models is maintained, that is, three-layer BP network is selected, the number of input layer neurons is 6, the number of hidden layer nodes is 13 and the number of output layer neurons is 1, that is, 6131 network structure (Li et al. 2016). Similarly, the data of 36 samples provided in Chapter 3 are used for analysis. In total, 5, 14, 22 and 27 samples were selected as test samples and the remaining 32 samples were selected as training samples. The network training parameters are set as follows:

In MATLAB, the data of the four test samples were input into the trained neural network to run the program. The comparison between the predicted value and the actual value of the test sample is shown in Table 3.

Table 6.3 BP network training parameters

Number of training	Training goal	Learning rate
5000	0.0000000001	0.01

According to the results, the difference between three of the four test samples is controlled within 0.002. Only one sample has a larger difference between the predicted value and the actual value. The relative error is 0.92%. However, it is still within acceptable limits (Table 6.4).

Table 6.4 Test sample actuals and predictors

Test sample	Actual value	RS-GA-BP model predictive value	Relative error
5	0.5833	0.5840	0.12
14	0.7500	0.7569	0.92
22	0.6250	0.6264	0.22
27	0.7917	0.7933	0.20

Model comparison In order to verify the accuracy and effectiveness of the RS-GA-BP-based prediction model, the relevant content of the model comparison was added. The RS-BP neural network prediction model without genetic algorithm optimization was compared. The accuracy and effectiveness of the RS-GA-BP prediction model were further tested and verified based on the predicted values of the training samples and the detected samples.

In order to establish a comparative relationship with the RS-GA-BP prediction model, the network structure of the two was maintained, and the three-layer BP network was selected. The number of neurons in the input layer was 6, the number of nodes in the hidden layer was 13 and the number of neurons in the output layer was 1, that is, the network structure of 6131. Data from 36 samples were analyzed. In total, 5, 14, 22 and 27 were selected as test samples and the remaining 32 were used as training samples.

Example exploration: The ultimate goal of theoretical research was to invest in real production practices. The validity and feasibility of the construction safety prediction model based on RS-GA-BP were proved. The model is used to predict the safety of a project under construction (hereinafter referred to as GY project), which provides a reference for future safety production management.

The GY project is organized by self-financing funds and is tendered by means of open tendering. The project is divided into two sections with a building area of over 70,000 square meters. One bid section: 3# building area is 12636m2 with 12 floors. 4# building area is 11574m2 with 12 floors. The building structure is a frame shear wall. The building area of the canteen is 5452m2. The ground is 5076m2 and the underground is 376m2. The building structure is a frame structure. The second bid section: 1# building construction area is 16166.19m2 with 17 floors. 2# building area is 13379.70m2 with 14 floors. 5# building area is 12286.06m2 with 13 floors. The building structure is a frame shear wall. Finally, HX Construction Engineering Co., Ltd. was determined to be the construction unit of the first section of the project. BH Construction Group Co., Ltd. SH Branch is the construction unit of the second tender of the project.

In view of the rationality of the indicators, the construction site was inspected on the spot. Project managers, safety management personnel, supervision management personnel, and technical operations personnel were investigated on the spot to make the data more objective. Data from one bid and two bids were obtained by means of face-to-face interviews, questionnaires, and field surveys. Among them, a1 is the work capacity of people at high places, a2 is the degree of safety protection, a3 is the construction site situation, a6 is the untrained worker, a8 is the organization command ability, and a10 is the safety material. The data acquisition process of the above six indicators is briefly introduced in conjunction with the related content set by the indicator problem.

The data is normalized and input into the RS-GA-BP based construction safety prediction model. The output of the first bid section is 0.7125, and the output of the second bid section is 0.5042. As a result, the decision-making attribute of the first bid section has a thousand-person injury rate of 0.7, and the decision-making attribute of the second bid section has a wound injury rate of 0.5.

6.4 Discussion

6.4.1 Construction Project Safety Pre-Control System

For the construction projects at different locations and in different locations, the main risk factors affecting their safety status are slightly different. Therefore, the safety accident sample is crucial for predicting the rationality and accuracy of the model. The selection of the number and quality of safety accident samples must be strictly controlled. However, the construction site of the construction project is highly dispersed. In a short time, it is difficult to collect data related to safety production of construction projects. Therefore, relevant data information of different projects should be stored at any time. The data information of different projects in different locations and at different times is summarized into the database management system in time. The integration of the database with the web server must be implemented. When the construction company makes security predictions, the Web server calls a large amount of data in the database management system. A good situation of multi-enterprise, multi-project, and information integration and sharing was formed. The safety management level of building construction was improved. The company's respective browsers, Web servers, and database servers together form the construction site safety management information system. The structure of the construction site safety management information system is shown in Figure 6.4.

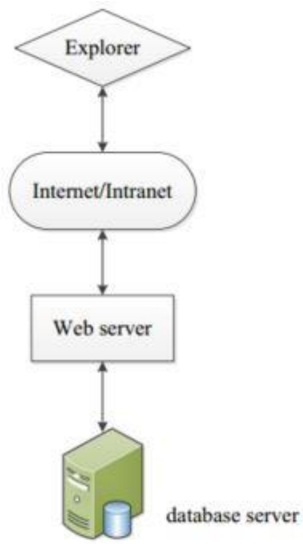

Figure 6.4 Structure diagram of safety management information system for construction site

The construction project safety pre-control system was initially designed. According to the mechanism of safety accidents, four main factors leading to safety accidents are extracted: human unsafe behavior, unsafe condition of the object, bad environment conditions and management defects. A risk factor system for construction safety production was established. The safety early warning control system takes the “4M” factor as the basic starting point and takes the construction project safety production risk factor system as the research object. Relevant data was collected. Then, the RS-GA-BP building construction safety prediction model is used to predict the construction safety status. The development trend of the accident is quantitatively described. Possible economic losses or injury rates are assessed. The impact of various risk factors on safety management is analyzed in depth. According to the process and results of the forecasting and evaluation, the status of the project of the construction company is analyzed and evaluated.

Furthermore, safety precaution measures are proposed. Targeted prevention and control measures are applied to different risk factors.

6.4.2 Analysis of Results of Building Construction Safety Prediction Model Based on RS-GA-BP

The RS-GA-BP-based construction safety prediction model was compared with the RS-BP-based construction safety prediction model. The results are shown in Table 6.5.

Table 6.5 Comparative analysis of model results

Number	Actual output	RS-BP prediction	Relative error %	RS-GA-BP prediction	Relative error %
5	0.5833	0.6450	10.578	0.5840	0.120
14	0.7500	0.7319	− 2.413	0.7569	0.920
22	0.6250	0.6521	4.336	0.6264	0.224
27	0.7917	0.8459	6.846	0.7933	0.202

As can be seen from Table 6.5, the rough set theory is used to reduce the risk factor system of construction. The BP neural network prediction model optimized by genetic algorithm has achieved good results and the convergence speed is improved. The accuracy and precision of the predicted results are high. The true state of construction engineering safety production is accurately predicted. Therefore, the prediction model based on RS-GA-BP net-work shows a strong advantage in the field of building construction safety prediction, which can effectively predict the safety status of building construction. In practice, construction safety analysis is guided.

6.4.3 Empirical Research Based on RS-GA-BP Predictive Model

Indicators should be reasonably designed, and the construction site was inspected on the spot. Project managers, safety management personnel, supervision management personnel and technical workers were investigated. Interviews, questionnaires and field surveys were combined to obtain data for one and two bids. a1 is the amount of work for people at high places, and a2 is the degree of safety protection. a3 is the construction site situation, and a6 is the workers without safety training. a8 is the organizational command ability, and a10 is the level of safety materials. Combined with the relevant content of the indicator problem setting, the data acquisition process of the above six indicators is briefly introduced.

The indicator a1 refers to the amount of work performed by people at high places. This is mainly achieved through face-to-face communication with managers (project man- agers, supervisors). The management knows the whole project very well. They can give a more accurate quantitative description of the high work volume involved in the whole project.

Among these indicators, a2 is the degree of safety protection. Different questions are set under this indicator, and different methods are used to investigate different people according to the nature of the problem. For example, the question ‘‘Do you use personal safety protection at work?’’ is to issue a questionnaire to a large number of workers on the construction site. The operator makes a choice among the four options ‘‘A. never used, B. generally not used, C. often used, D. always used.’’ The questionnaire was recycled. The construction site was surveyed to obtain information about such problems as ‘‘the protective measures for stairway entrance, elevator well entrance, reserved holes and pits, the improvement of the protective shed at the passage entrance, the use of safety labor supplies such as safety caps, rubber shoes and insulating gloves for workers.’’ At the same time, combined with the interview and communication with the corresponding operators, the data are consistent with the reality to the greatest extent. Such questions as ‘‘whether construction enterprises are equipped with basic teams for engineering facility rescue and emergency management and rescue’’ are mainly obtained through interviews and exchange with management personnel, and on-site investigation is conducted to confirm whether the situation is true.

Safety slogans such as safety warning signs and accident warning signs at the construction site are reasonably set. Site layouts such as construction machinery and materials are regulated. The layout of on-site fire prevention facilities, the specific distribution line plan and system diagram of temporary power consumption should be consistent with the actual situation of the construction site. The problems are mainly obtained by on-the-spot investigation. At the same time, combined with the interviews with managers and operators, the data are in line with the actual situation. The problems of ‘‘construction site life management system, health management system, and establishment and implementation of public security management system’’ are mainly obtained through interviews with management personnel, and on-site inspection and confirmation of operators.

6.5 Summary

As an important pillar industry of China's national economic development, the construction industry's sustained and benign development directly affects the economy. However, China's current construction safety management level is far lower than that of foreign developed countries. The safety production situation in terms of the number of accidents, the output value of 10 billion yuan and the death rate is very serious. The theory of safety accident cause and the theory of hazard identification are taken together as the mechanism theory of safety accidents. The four necessary factors for a security incident are analyzed: human, machinery matter, environment, and management. Combined with the hazard source identification theory, the risk factors in the safety production of construction projects are comprehensively analyzed. A risk factor system for construction safety production was established. This has certain guidance and reference for the safety management and prediction of building construction.

There are numerous risk factors for the building safety accidents. Through a large amount of data, its inherent regularity is discovered. The validity and accuracy of neural network training also need to be based on a sufficient number of training samples. Due to limited time, personal energy and ability, the number of data collected on construction safety accident cases is limited. This will affect the rough set attribute reduction and the training of the BP network. This situation also reflects the serious problems in the construction, induction and storage of data in China’s construction industry, so the safety production database should be established and improved. As a result, the information security management of building construction is realized.

6.6 Illustration of Case Study 3

Case study 3 examines the third level of CTO in architecture linked with society as the environment. In this case study, we consider ‘accidents’ in building construction is the emergence. In complexity science, emergence occurs when an entity is observed to have properties its parts do not have on their own (Corning, 2002). These properties or behaviors emerge only when the parts interact in a wider whole. For example, smooth forward motion emerges when a car and its driver interoperate, but neither part can produce the behavior on their own. For the same reason, accidents only emerge when building workers interact in building construction, thus ‘accidents’ in building construction is the emergence.

Emergence plays a central role in theories of integrative levels and of complex systems. For instance, the phenomenon of life as studied in biology is an emergent property of chemistry. Case study 3 aims to solve building workers’ safety problems in building construction, the above analysis inspires us the key to solving workers’ safety problems is avoiding the accidents may occur in building construction, therefore we use BP Neural Network Algorithm to predict accidents so that to avoid them.

Chapter 7 Discussion

This chapter consists of two parts, the first part discusses the applications and implications of CTO in the three case studies (from Chapter 4 to Chapter 6). The second part discusses CTO' s contributions to Knowledge Science, in which the relations between 'creative intelligence' with 'knowledge intelligence' and the contradiction between them are pointed out, how to solve the contradiction seems a tough problem in knowledge science. But fortunately, this contradiction is not unsolvable, CTO might be a good solution as it contributes to facilitating 'effective creativity' in process of knowledge creation.

7.1 Discussion of Three Case Studies

In this research, I compare the Concept Topology Optimization design approach with other design approaches in reductionism, design approaches in reductionism break the system down to its pieces to reason about it from the properties of these pieces. It tries to analyze and describe the complex phenomena of architecture in terms of parts that exist on a simpler or more fundamental level. It pays attention to the parts of the whole and assumes that all higher-level phenomena can be understood based on a combination of the lower level features.

Therefore, architecture design approaches in reductionism results in architecture made up of isolated components that interact in a pre-determined linear way. In my thesis, Concept Topology Optimization is introduced into architecture as a CAS, it breaks the static and certain architectural design thinking approach and then open up new directions for architectural design-dynamic, continuous and changing thinking approach. Architecture design is difficult but unique as it has social, artistic and technological aspects. In this thesis, we conduct the first case which is actually concerning green innovation, space innovation and safety innovation.

7.1.1 Applications and Implications of CTO in Case Study 1

In this case, we apply the first level of CTO, in which optimization does not change the original concept but requires the ability of abstraction and review.

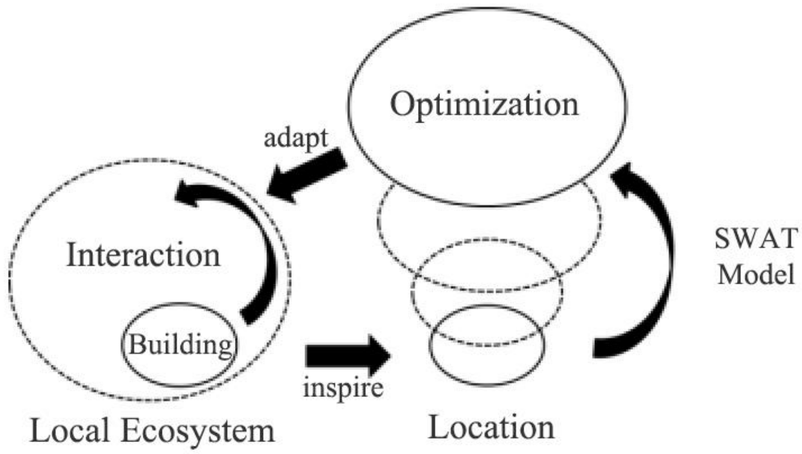

Figure 7.1 Model of CTO in Case Study1

This case study links ecosystem with architecture as the changing environment and narrow into a manageable research question: How to apply Concept Topology Optimization design approach in aiding in architecture location design that make architecture more environmental to local ecosystems? To answer this question, we need to make 'environmental' more well-defined, thus we firstly analyse the interaction between building and wetland park is water, then we use SWAT Model to make quantitative analysis of water quality for designing the expo architecture location.

Through the location design project in LinGang wetland park, it suggested that the first level of CTO may stimulate out-of-the-box thinking and encourage designers to review the design concept and even to redesign the existing or familiar things. Therefore, this level of CTO prefers the optimization of 'concept depth'.

7.1.2 Applications and Implications of CTO in Case Study 2

In this case, we apply the second level of CTO, in which optimization includes analogy, synthesis, blending or more general forms of creative transformation of existing knowledge or concepts. After the topology optimization, the changing inheritance relationship can still be found in the new concept and the logic process of the concept optimization can be clearly seen.

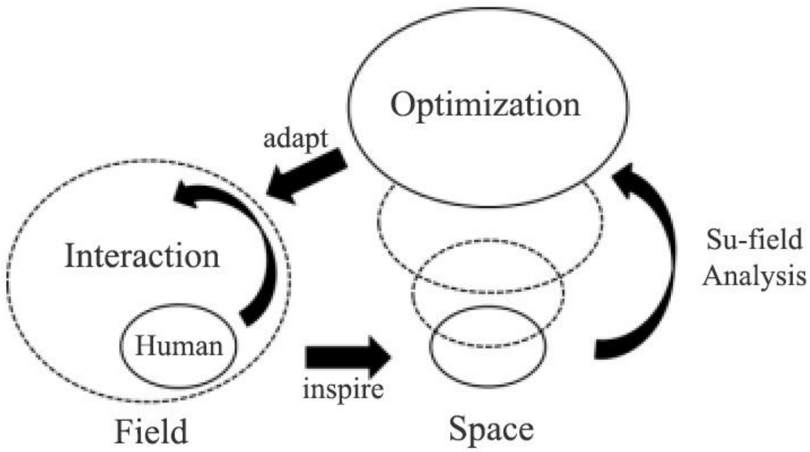

Figure 7.2 Model of CTO in Case Study 2

This case study links human with architecture as the changing environment and narrow into a manageable research question: How to apply Concept Topology Optimization design approach in developing a new method for more creative human-centred architecture space design? To answer this question, we present an innovative 'field' for human as an analogy to the 'field' in Su-field analysis model.

This level of CTO may be the easiest to understand and apply, Case study 2 conduct a controlled experiment which demonstrates the effectiveness of this method by measuring idea quality and quantity. In the experiment, we observed the method in case study 2 stimulated logical and orderly concept optimization and may have the ability to help participants overcome mental blocks in concept generation process. Therefore, this level of CTO prefers the optimization of 'concept breadth'.

7.1.3 Applications and Implications of CTO in Case Study 3

In this case, we apply the third level of CTO which is accompanied by the tearing, cutting, and blocking on the deformation of the second level. This optimization destroys the overall structure of the original concept to some extent, belongs to the scope of emergence.

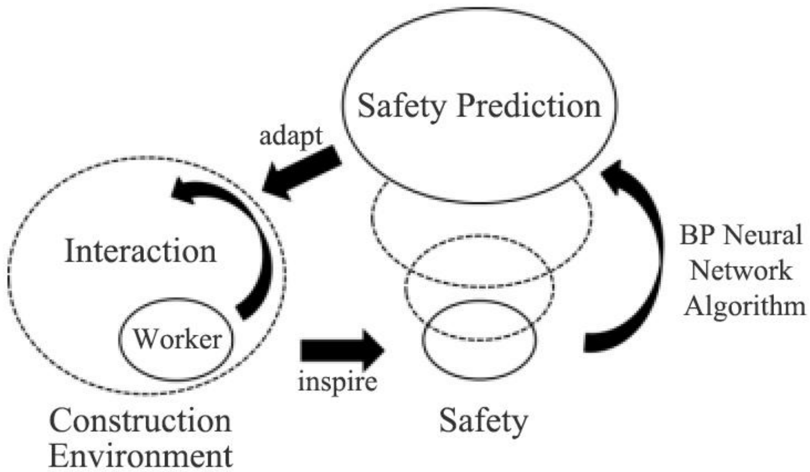

Figure 7.3 Model of CTO in Case Study 3

This case study links society with architecture as the changing environment and narrow into a manageable research question: How to apply Concept Topology Optimization design approach to solve building workers' safety problems in building construction? To answer this question, we firstly consider 'accidents' in building construction is the emergence. In complexity science, emergence occurs when an entity is observed to have properties its parts do not have on their own. Emergence plays a central role in theories of integrative levels and of complex systems. Therefore, it inspires us the key to solving workers' safety problems is avoiding the accidents may occur in building construction, thus we use BP Neural Network Algorithm to predict accidents so that to avoid them.

BP network algorithm which is a typical tool in complex science to acquire 'emergence' in construction safety design. In fact, there are other optimal approach may have the possibility to help designers acquire 'emergence' in concept optimization process. This level of CTO is not easy to apply but it's necessary to figure it out as 'emergence' is the most unique characteristic of architecture as a CAS, which may bring the most promising creative ideas required for innovation as 'emergence' occurs only when an entity is observed to have properties its parts do not have on their own. These properties or behaviors emerge only when the parts interact in a wider whole.

7.1.4 Summary

Through CTO design thinking approach, we developed three creative design methods in this thesis, the first common point among the three methods is that they all guide designers to find out situations based on design agents' interaction with their environment, the second common point is that they all utilized verified theory or tools as 'ground structure' to conduct concept optimization. As a result, the first common point may help designers find the 'Right' situation and the second common point may stimulate designers' persistence to the 'Best' solution. The two characteristics fit the creativity scan model presented by Darrell Mann (2018) shown in Figure 7.4.

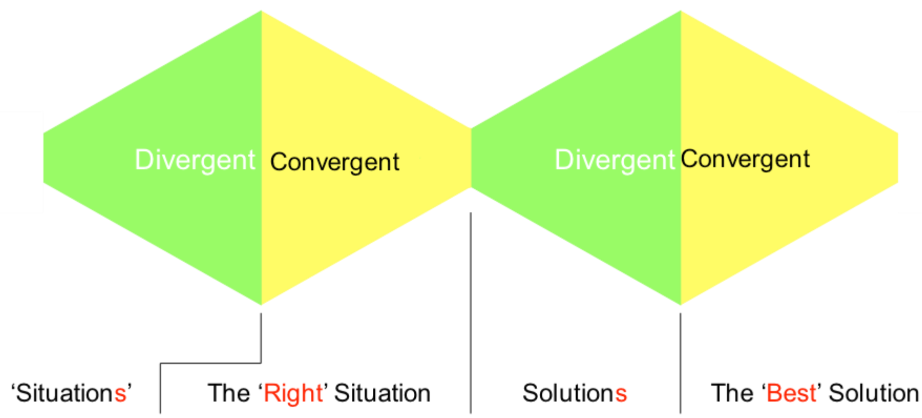

Figure 7.4 Creativity Scan Model (Darrell,2018)

In this model, Darrell Mann presents 'Effective creativity' requires at least two of these divergent convergent cycles, one is to finding out the 'Right' situation' and the other one is to acquiring the 'Best' solution. Obviously, CTO design thinking approach satisfies these requirements, thus CTO design thinking approach should be effective in promoting 'Effective creativity' which has a more common term- innovation.

7.2 Contributions to Knowledge Science

School of Knowledge Science in JAIST fuses learning fields at the cutting edge of knowledge creation in wide research fields with the aim of discovering mechanisms that create, accumulate, and utilize knowledge and generating ideas on the design of our future society. The aim of knowledge science deeply toughs me, thus the contributions to Knowledge Science of this thesis are discussed particularly about knowledge creation.

7.2.1 An Attempt to Promoting Knowledge Creation in Complex Science

Creativity and innovation are at the cutting edge of knowledge creation, we have a long way to go to release our creative energy as there are many blocks to creativity (David, 1998 & Von Stamm, 2008). Especially in complex science which builds a new knowledge system which is more complex and dynamic (Snowden, 2002) in methodology and thinking approach. Knowledge creation usually involves the three parts: 1. A mechanism of introducing variation to already existing knowledge 2. A consistent selection process 3. A mechanism for preserving and reproducing the selected variations (Sherif & Xing, 2006). In CTO model, all the three parts can be found, the first part is analyzing interaction between agent and environment, the second part is the ground structure and the third part is the adapting process in CTO model.

Therefore, this thesis attempts to build effective interaction-based design thinking approach that support designers in 'making knowledge productive' and take into account the ways in complex science. Three case studies have suggested that CTO design thinking approach may stimulate effective and creative architecture design. Moving forward, such a hypothesis still needs to be further tested with more experimental data

7.2.2 Contradiction Between 'Creative Intelligence' & 'Knowledge Intelligence'

Darrell (2018) undertook a fifteen-year program of research into 'effective creativity', which revealed that creative process needs two separate aspects of intelligence: 'creative intelligence' and 'knowledge intelligence'. 'creative intelligence' is how creative ideas we generate, 'knowledge intelligence' is how much stuff we know, Figure 7.5 shows the contradiction between 'creative intelligence' & 'knowledge intelligence'.

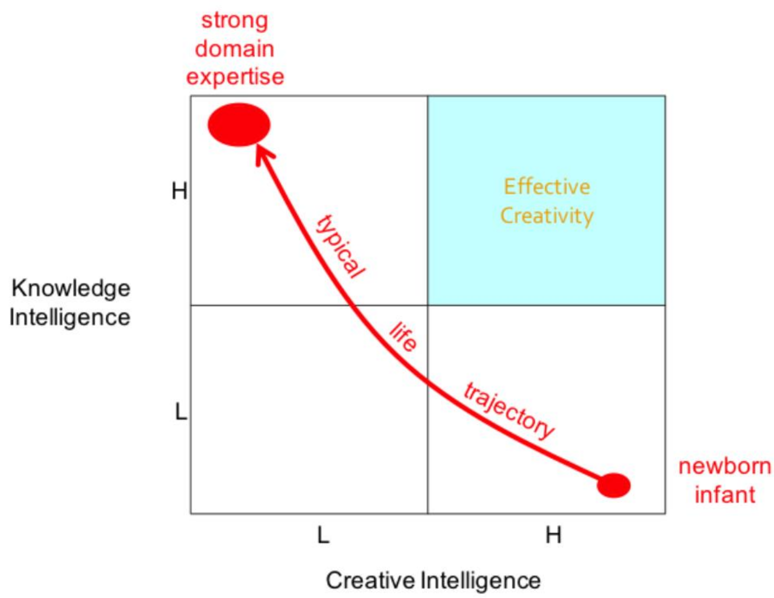

Figure 7.5 ‘Creative’ Versus ‘Knowledge’ Intelligence (Darrell, 2018)

In this interesting theory, we are all born with unconnected neurons inside our brain, so that we can image things in lots of ways and our ‘creative intelligence’ are at its height. When we grow up and have an amount of knowledge, neurons in our brain get connected to others, and get reinforced into immovable. As a result, the more knowledge we acquire, the more neural pathways we make rigid, and hence the less creative potential we have. This contradiction is inherent but we can solve it by seeking ‘effective creativity’.

Chapter 7.1 have indicated that CTO design thinking approach should be effective in promoting ‘Effective creativity’ as it satisfies the requirements of Creativity Scan Model very well. Meanwhile CTO design thinking approach provides a novel process for concept optimization, for instance, in case study 2, experienced architects with good ‘knowledge intelligence’ set Su-field analysis as the ground structure, and then unexperienced designers or users with little ‘knowledge intelligence’ but good ‘creative intelligence’ can generate their effective and creative architecture space ideas by following the ground structure in CTO design thinking approach. That may be another reason why CTO may lead to ‘effective creativity’, thus the contradiction between ‘creative intelligence’ and ‘knowledge intelligence’ can be solved. In addition, that characteristic of CTO may makes itself effective in Co-design (Frow et al., 2015).

Chapter 8 Conclusion & Future Work

In this thesis, 'Concept Topology Optimization' is introduced into architecture as a CAS, it breaks the static and certain architectural design thinking approach and then open up new directions for architectural design—dynamic, continuous, changing design thinking approach.

To answer for SRQs and MRQ presented in Chapter 1, we summarize the answers as followings:

SRQ 1: What are the characteristics by acknowledging architecture as a complex adaptive system (CAS)?

- Define components in architecture as agents which are active, living entity and capable of adapting to environments.
- The interactions between individuals and environment is the driving force for the evolution of the system.
- It provides designers with a dynamic and evolutional view of architecture.
- It introduces the concept 'emergence' which is particular when acknowledging architecture as a complex adaptive system

SRQ 2: How can designers utilize the characteristics by acknowledging architecture as a complex adaptive system (CAS) to develop new design approaches for architecture?

Firstly, designers should acknowledge architecture as a complex adaptive system instead of understanding the nature of architecture by reducing it to independent individuals, or to simpler or more fundamental things. Secondly, designers can build their own interaction-based design approaches by defining components in architecture as agents which are active, living entity and capable of adapting to environments.

In this thesis, we present 'Concept Topology Optimization' design approach as an attempt. Since the birth of architecture, architects have been combining various social elements and resources in form and space. Especially when we acknowledge architecture as a CAS, which is radically different from the static architecture system. Designers Topology is a study of continuity mathematics. The application of topological principles in architectural design can led to a smoother, more continuous design of combining elements and resources. This continuous integration does not obliterate the differences between the elements. Although they are not reproducible and homogeneous, under the premise of maintaining the differences of elements, continuous integration unifies heterogeneous elements into one system. Today, with the diversity of social resources and diversified interests, how to integrate these factors in the form of architecture is the focus of architects.

Topology can attract our attention also because it involves the flexibility of form and has an important impact on the design process and the establishment of the form. The special part of the design process is the form of deformation and “emergence”. The “emergence” is not a delusion nor an assumption, but a result that continues from the beginning of the deformation to the final result. Therefore, we apply the topological principles in architecture concept generating process and propose the design thinking approach ‘Concept Topology Optimization’ for architecture design.

SRQ 3: What can examine the effectiveness of the new design approaches?

Case study method can examine the effectiveness of the new design approaches as it is defined as an intensive study of a single unit with an aim to generalize across a larger set of units and can examine complex phenomena in the natural setting to increase understanding of them.

In this thesis, we present three case studies to demonstrate the effectiveness of ‘Concept Topology Optimization’. More specifically, Case study 1 in Chapter 4 demonstrate the effectiveness of differential homomorphic topology optimization by empirical inquiry. Case study 2 in Chapter 5 demonstrate the effectiveness of homomorphic topology optimization by conducting a controlled experiment. Case study 3 in Chapter 6 demonstrate the effectiveness of non-homeomorphic topology optimization through multiparty consultation, empirical analysis and model comparison.

MRQ: What are the effective design approaches for architecture as a complex adaptive system?

In this thesis, ‘Concept Topology Optimization’ is presented as an effective design approach for architecture as a CAS and implied as an effective tool for knowledge creation.

Acknowledging architecture as a CAS is like a new entrance for researchers to access architecture design. 'Concept Topology Optimization' design approach is one 'key' to open the new entrance.

However, it's possible that there are other design approaches and these approaches should have the characteristics: interaction-based, capable of adapting, dynamic and capable of developing emergence.

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Publications, Awards & Activity

Papers Published in Journals (Indexed in Sci & Scopus)

1. Tao Shen, Yukari Nagai，Chan Gao. Design of Building Construction Safety Prediction Model Based on Optimized BP Neural Network Algorithm. (Reviewed) *Soft Computing*, (2019) DOI :10.1007/s00500-019-03917-4
   This journal paper is the main content of Chapter 5 in my doctoral thesis.
   This journal paper utilizes the design approach presented in my doctoral thesis.

2. Tao Shen, Yukari Nagai, Xin Chen. Ecological Environment Based on the Expo Architectural Design Project. (Reviewed) *Ekoloji* 27(106): e601. (2018)
   This journal paper is the main content of Chapter 4 in my doctoral thesis.

3. Tao Shen, Yukari Nagai，Chan Gao. Improve Computer Visualization of Architecture Based on the Bayesian Network. (Reviewed) *Computers, Materials & Continua*, 58(2), 307-318. (2019)
   This journal paper utilizes the design approach presented in my doctoral thesis.

4. Tao Shen, Yukari Nagai，Chan Gao. Optimal Building Frame Column Design Based on the Genetic Algorithm. (Reviewed) *Computers, Materials & Continua*, Vol.58, No.3, pp.641-651. (2019)
   This journal paper utilizes the design approach presented in my doctoral thesis.

International Conference Proceedings

1. Tao Shen, Yukari Nagai, Eunyoung Kim. A New Method for Architecture Space Design Based on Substance-Field Analysis. 2018 International Conference on Construction, Aerotropolis and Environmental Engineering, (Reviewed). In IOP Conference Series: Earth and Environmental Science, vol. 233, no. 2, p. 022027. IOP Publishing, November 23-25, 2018, Taoyuan, Taiwan. (Oral presentation, Indexed in Ei Compendex)
   This conference paper is the main content of Chapter 4 in my doctoral thesis.

2. Tao Shen, Yukari Nagai. Effects of Unfolding Techniques as Design Stimuli in Building Design. The Fifth International Conference on Design Creativity, (Reviewed). In DS 89: Proceedings of The Fifth International Conference on Design Creativity (ICDC 2018), pp. 15-22. February 2018, University of Bath, Bath, UK. (Oral presentation, Top Paper Award)
   This conference paper utilizes the design approach presented in my doctoral thesis.

3. Tao Shen, Yukari Nagai. Application of Original Ecological Design in Architectural Space Innovation Design. 2018 2nd International Conference on Social Sciences, Arts and Humanities, (Reviewed). pp. 809-813. June 2018, Tianjin, China. (Oral presentation, Indexed in CPCI)
   This conference paper is the constituent content of Chapter 6 in my doctoral thesis.

4. Xin Chen, Tao Shen. A Novel Clothing Design Method for Children with Autism Spectrum Disorders Based on Fun Computing Theory and Substance-field Analysis (Reviewed). In IOP Conference Series: Materials Science and Engineering (Vol. 520, No. 1, p. 012019). IOP Publishing. February 22-24, 2019, Nice, France. (Oral presentation, Indexed in Ei Compendex)
   This conference paper utilizes the design method presented in Chapter 4 of my doctoral thesis.

Awards

1.Top Paper award: Tao Shen, Yukari Nagai. Effects of Unfolding Techniques as Design Stimuli in Building Design. The Fifth International Conference on Design Creativity (ICDC 2018)

2. JSSD Encouragement Prize in the 3rd Branch (2019)

Activity

Initiate the special issue 'Innovation in Architecture Design' in *International Journal of Architecture, Arts and Applications* and became the Lead Guest Editor.