Generative Architectural Design and Complexity Theory

Christiane M. Herr Dipl.-Ing. (Arch), MArch (cand.)
Department of Architecture, Hong Kong University.
e-mail: candyhk@hkusua.hku.hk

Abstract

During the past decades, complexity theory has evolved as a new discipline that provides a broad scientific perspective towards dynamic real-life phenomena, challenging the classical linear worldview as well as simple cause-and-effect-style Newtonian physics. For architects, the advent of this new science offers the challenge as well as the chance to reconsider common design approaches and to invent new strategies based on the new paradigms. The actual application of complexity theory to architectural design, however, results in a fundamental dilemma: How can a reflective, ultimately retrospective body of thought (complexity theory) be applied to prospective design challenges (architecture)? Being part of a current MArch thesis project, the proposed paper focuses on this general dilemma between architectural design and complexity theory and discusses actual as well as potential future generative architectural design approaches involving complexity theory. Generative design strategies commonly apply algorithmic methods and formalisms, which can conveniently produce and deal with high levels of complexity. Complexity describes general properties of a system and can be further dissected into several modes: epistemic, ontological and functional complexity. This taxonomy offers insights into generative design applications, which have mostly focused on a limited set of complexity modes. Besides complexity generated by sheer numbers, aspects like functional or hierarchical complexity offer further perspectives on generative systems, processes and output. Considering these aspects of complexity theory, future challenges to generative architectural design can be predicted.

1. Introduction

During the past fifty years, a major extension to classic natural sciences has changed many views on natural phenomena in general, summarized in the discipline called *complexity theory*. While these changes have affected mathematics, physics and biology for decades, the underlying thoughts are only beginning to be realized in other areas including history, economy or architecture. Complexity theory focuses on complex relationships of elements, which are not random but subject to mechanisms that generate order on various levels of organisation. Traditional science emphasizes stability, order, uniformity and equilibrium and focuses on closed systems and linear relationships. In contrast to that, complexity theory brings attention to disorder, instability, diversity, disequilibrium and unstable equilibria, and nonlinear relationships, which describe temporality and causality found in real-life phenomena more accurately than traditional scientific methods.

Venturi [22] proposed a first theory about complexity and contradiction in architecture in 1966. Then, complexity theory was still in its infancy, but the central concerns of Venturi's thoughts were the same as ours today: the search for a design approach that could work in real-life situations instead of isolated and idealized scenarios. Architecture has traditionally

drawn on rigid forms of order that tended to be indifferent to environmental influences. Venturi's search was motivated primarily by the desire to find alternatives to modernism's emphasis on the linear and the grid-like with its strong tendency to ignore conflicts and difficulties arising out of complex situations. His search, coupled with an interest in scientific complexity theory, has been taken up again during the past decade. A number of architectural theorists have written about complexity in architecture, among them Jencks [12], Eisenman [7] and Lynn [15], but attempts to use complexity theory in architecture have rarely ventured beyond rather diagrammatic and iconic applications. After the novelty of the subject has worn off, the main question still remains unanswered: How can architecture be related to complexity theory? When looking at the characteristics of generative architectural design and complexity theory more closely, the generative approach to architectural design sticks out as a promising strategy.

2. Generative Architectural Design

Generative design is still a relatively new approach to architecture. Relevant terminology is yet based on rather vague notions, and encompasses a broad range of loosely related methodologies. In general, generative design can be described as a design strategy that differs from other design approaches insofar that during the design process the designer does not interact with materials and products in a direct way, but via a generative system of some sort [8]. In this paper, generative system refers to digital, computer-aided generative systems that are most typically but not necessarily developed by architectural designers themselves. Generative architectural design is a specific approach to design problems in the architectural field, and it reflects characteristic problems in design in general.

Design problems in architecture are unique, open-ended and ill-structured [19]. Therefore, solving design problems always requires problem-specific and to some extent experimental methodology. The uniqueness of architectural problems does not allow architects to solely rely only on predefined methodologies or previous solutions to similar problems. Though approved design knowledge is often re-applied to specific sub-problems, overall approaches in architectural design are typically experimental. To avoid undesired side- or after-effects, architects takes on the responsibility to evaluate all known factors involved in a design project that might lead to unwanted outcomes in both physical (structural, functional) and ethical (social) sense. Architectural problems are complex and characterized by a wide range of determining, partly unknown or subconscious factors on various levels, ranging from local building codes to aesthetic aspects. Architects and designers are experienced in solving these problems, which due to their complexity require the architect's reasoning, guessing as well as intuitive decision-making.

Defining and understanding given design problems requires conceptions of possible solutions: information needed to understand a problem depends upon the designer's idea for solving it [19]. Conceiving and developing a solution scenario at the same time is tied to a conception of the future: During design processes, images of a desirable future are developed in order to guide a process of planning and action that will eventually approximate a selection of those images. Design processes are to some extent directed towards utopian design ideals, which develop out of predictions as well as desires and hopes.

Today, generative techniques are primarily applied to the challenge of generating variance

during a design process (see for example Spuybroek, *Off the Road – 5speed*, in [1], pp. 56-61). Even though sets of possible solutions can often be easily determined (automatically generated), human selection is typically still needed to pick the most appropriate one(s) (see [8]). This can be (at least partially) explained with responsibilities resulting from unpredictable – complex – consequences of design decisions. In the context of this challenge, complexity theory can offer valuable insights. Due to lacking social and contextual knowledge and reasoning capabilities, computational systems are not (yet) put in charge of bearing such responsibilities. To direct generative processes and to evaluate and select from variants, feedback from the human architect is hence still required. Generative systems that are yet designed to select from generated sets commonly follow one of the following two strategies. They either use sets of general constraints to regulate generative processes, as for example selection criteria in evolutionary design systems. Such sets are often highly simplified and to not necessarily embrace all relevant aspects of functional/structural/social etc. responsibilities. They are hence mostly found in experimental settings or as explorative aids in early design stages. The other strategy retains generation and variance selection merely to superficial, e.g. ornamental design aspects, which are unlikely to produce unpredictable and hence undesired complex interferences with a building's functions. A potential third, more open strategy might be possible: this strategy draws on complexity theory and will be discussed in the following.

3. Complexity Theory

Within the past three decades, complexity theory has evolved from describing properties of specific given systems into a broad area of research in science with applications ranging from economics to physics. Since there is currently neither a consensual general definition of complexity nor a unified theory, complexity as a scientific interest is best explained in relation to the history of the field [11]. Complexity theory as a scientific area of study developed as a response to Newtonian linearity being the exclusive scientific paradigm, coupled with a reductionist approach prevalent in science until recently [18]. Newtonian science is based on the assumptions that physical and mathematical laws are essentially simple and straightforward like the ones proposed in Newton's *Principa Mathematica* in 1687. Time is assumed to be irrelevant to natural phenomena, so that all processes are entirely reversible. During the 20th century, these views have been challenged by a number of theories and discoveries, first of all Darwin's evolutionary theory, followed by Wiener, von Neumann and many others. Time has been discovered to play an essential role in irreversible processes, resulting in a renewed interest in history as determining the present (see [6]).

In addition to linear (and therefore strictly predictable) phenomena, complexity theory has opened up views on the tangled and more complicated causalities involved in systems formed by large numbers of interdependent elements. Complexity is observed in systems where many independent and varied elements interact in intricate organisational configurations, typically in a massively parallel manner. Examples include chemical reaction cycles, anthills and cities. Typically, complex systems are *open* – receiving or exchanging energy with their environments. Thus, complex systems are able to display complicated dynamics unlike energetically *closed* systems that will settle into stable equilibria. While it describes the qualities, not the quantities of a particular type of system (given systems can be characterized by its compositional, structural and functional complexity), complexity theory does allow for general statements about the system's behaviour. Among the most characteristic properties of

complex systems are self-organisation, nonlinearity, threshold phenomena or unstable equilibria (see [16]). A complex system's properties are relative to the observed scale – to study a single ant, for example, does not reveal the dynamics of an entire anthill. Thus, complexity theory serves as general description framework for many phenomena observed from more holistic scientific viewpoints. It represents a theoretical foundation to a vast number of more specific scientific fields, such as dynamical systems theory, fractal or recursive relationships, thermodynamics, and many others. These strategies are used as toolbox in generative design approaches.

Though definitions of complexity are numerous, rather vague and general, Rescher summarises characteristics of complexity as follows (see [20], p. 9):

Modes of Complexity:

Epistemic Modes: Formulaic Complexity
- Descriptive Complexity (length of the necessary amount of description)
- Generative Complexity (length of the recipe needed to produce a system)
- Computational Complexity (time and effort involved in solving a problem)

Ontological Modes: Compositional Complexity
- Constitutional Complexity (number of elements in a system)
- Taxonomical Complexity / Heterogeneity (number of types of elements in a system)

Ontological Modes: Structural Complexity
- Organisational Complexity (different modes of interrelationship between elements)
- Hierarchical Complexity (elaborateness of hierarchical relationships)

Functional Complexity
- Operational Complexity (variety of modes of operation or functioning)
- Nomic Complexity (elaborateness and intricacy in the laws governing a system)

3.1 Complexity and Prediction

Classical science relies on a linear world model, which renders predictions relatively exact and easy to make. With the rise of complexity theory, these views had to be adjusted. While simplified versions of reality may be described using traditional linear explanation models, the greater part of observed phenomena cannot be reduced to simple elementary behaviours without losing their essential characteristics. This sensitive dependence on environments renders complex systems difficult to isolate, model or reproduce for experimental purposes. Nonlinearity and their characteristic dynamics render complex systems hard to predict in the short term, and impossible in the long term – a well-known example for this problem is weather forecasting. However, complexity theory is also applied to prediction tasks (see [23]). Since complexity theory shows how limited possibilities of predicting dynamical systems are, there cannot be any case-based predictions related to specific future situations. Instead of exact, case-based prediction, an alternative based on stochastic observations is used: In order to characterize a system's ability to resist and adapt to external disturbance, system models are developed with as much detail as possible. These models are then tested for stability against random changes within simulated environments. Thus, predictions for complex systems are mostly based on identifying a specific system's properties in general rather than

predicting their exact future state or behaviour. Predictions are therefore based on statistical evaluations and large numbers of samples, and – similar to other statistical methodologies - only describe probabilities of future developments. As is known, though probabilistic data suggests prospective projections, it is not an entirely reliable planning basis.

4. The Relationship of Architecture and Complexity Theory

Complexity theory emerged out of a changing scientific context brought on by the general realisation of the shortcomings of classical Newtonian science. Rather than presenting completely new discoveries, complexity theory offers a new viewpoint on many known, but hardly understood phenomena, in particular those patterns and processes found in nature. Natural patterns and growth processes often exhibit emergent order, which can be observed at different scales in societies of elements that act in a massively parallel manner. In architecture, naturally grown structures have long been appreciated and imitated, often attributed with a presumed affinity to human beings (see [12]). This appreciation, however, was overpowered by modernist thinking, which condemned complex structures in favour of simplistic approaches. After a century of linearity and determinism in science and technology, the change of perspective on complex phenomena allows architects to reconsider growth processes in architecture, e.g. city development and building morphologies. Besides an interest in aesthetics derived from natural types of order, architects as well as engineers have explored ways of joining bottom-up approaches with the top-down planning requirements of stability and permanence (see [2]). For the extension to the Victoria and Albert Museum in London, Balmond refers to chaotic spirals to develop a columless form and structure.
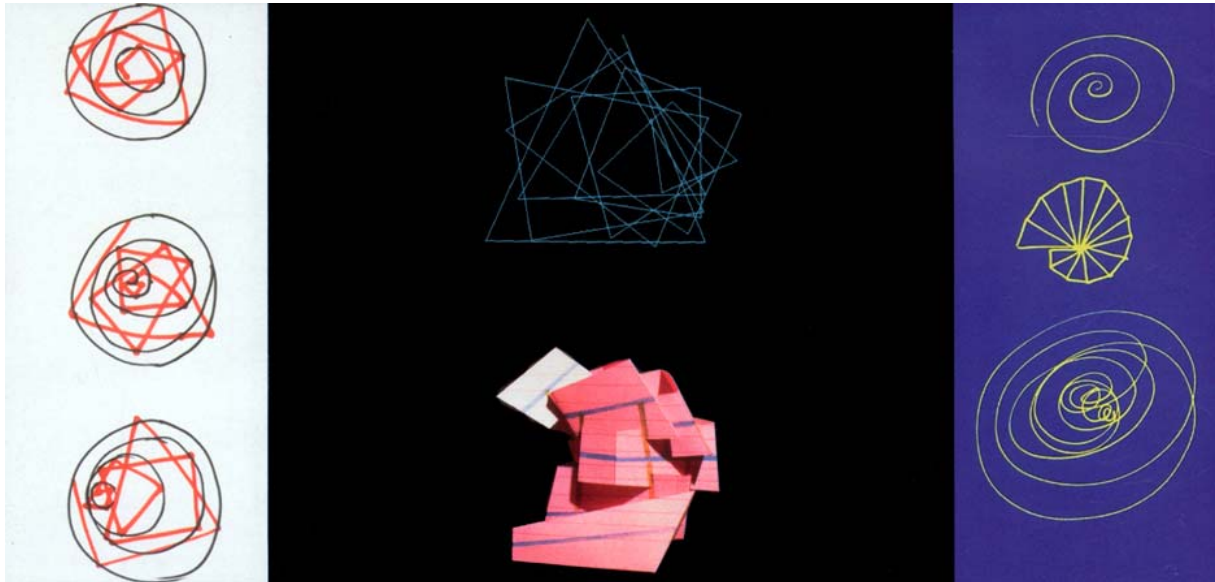

Figure 1: Cecil Balmond: Victoria & Albert Museum Extension (with Daniel Libeskind)

Architecture relates to current interests and views dominating society, and generally perceives its role as reflecting and propagating scientific and cultural paradigms [10]. While architectural modernism developed out of a fascination for machines, technology and science, it also inherited many problems resulting from over-generalisation of design problems. Architectural movements since the 1960s have attacked modernism for this reason, but it still holds as the dominant paradigm in architecture. Even though architects have introduced

complexity theory into the architectural discussion, traditional ways of thinking and designing have not changed much. Architects typically use top-down design strategies, since this is thought to ensure efficiency, economy and control in developing design solutions. Order as found in complex systems, on the contrary, develops without planning out of bottom-up processes [13]. Since architecture traditionally uses the former approach to design, most references to complexity theory have so far been retained to a metaphorical or iconographic level.
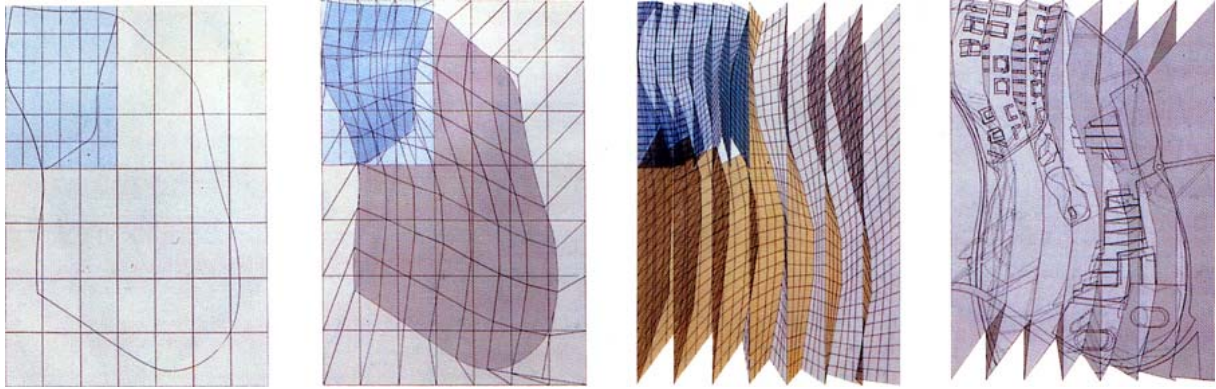

Figure 2: Peter Eisenman: Rebstock Park (Frankfurt) Masterplan, 1993

In his masterplan for Rebstock Park (Frankfurt), Eisenman uses folding metaphors in his design approach, graphically and metaphorically referring to diagrams derived from catastrophe theory that describe sudden changes in dynamic system developments (see figure 2). Showing an even more iconic approach, Jencks (figure 3) refers to complexity theory by directly translating diagrams and images depicting strange attractors and other complex phenomena in the design of his landscape architecture.

Figure 3: Charles Jencks and Maggie Keswick: Garden, Dumfriesshire, Scotland.

However, architectural problems usually involve complexity in the form of surrounding city fabric, building techniques, politics and unpredictable changes in the course of design processes, communication and building life. In order to make use of complex forms or systems in architectural design, tools are needed that can handle complex forms or relationships. Generative architectural design developed as an answer to these needs. When comparing the history of generative architectural design with Rescher's [20] modes of complexity, close parallels become obvious. Most applications of generative architectural design in the past have focused on variations or combinations of constitutional and taxonomical complexity in generating variance (e.g. L-systems, shape grammars, parametric design, data mapping techniques and the like). As an example, figure 4 shows a roof structure based on the generation of a large number of simple elements constrained by a continuous global alignment rule.
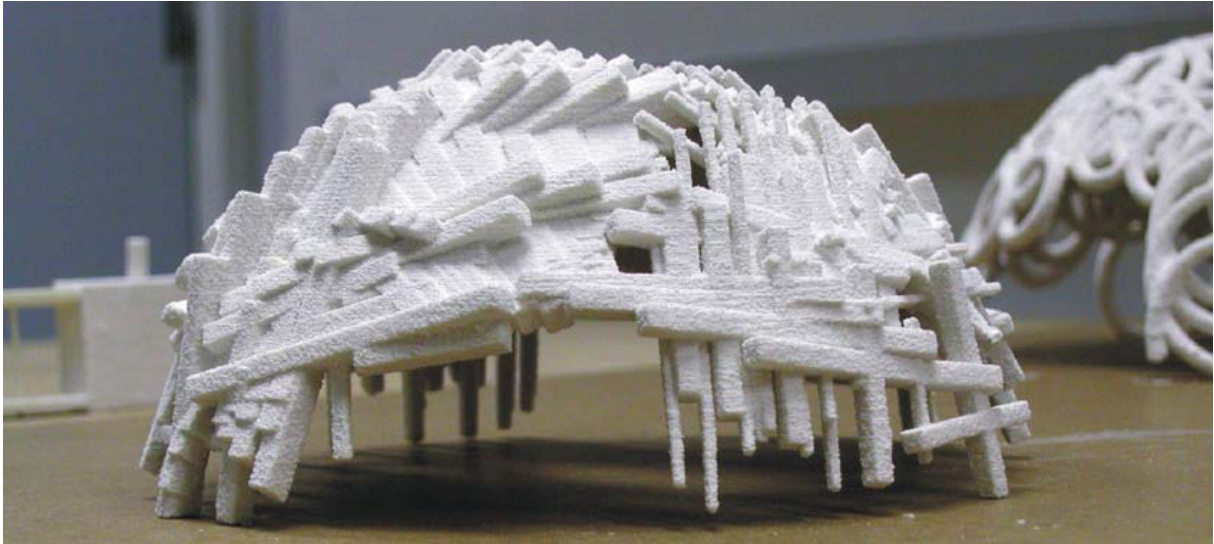
Figure 4: Generated roof structure (rapid prototype)

Only few generative architectural design approaches deal with other kinds of complexity such as evolutionary design or cellular automata. While there are generative approaches to hierarchical and operational complexity (e.g. emergent and self-organizing systems), they have not been used in architecture yet.

4.1 The Dilemma of Generative Architecture and Complexity Theory

The central conflict between architectural design and complexity theory is a consequence of the nature of both disciplines: scientific theory is an inter-subjective tool to observe and explain, while design is the exact opposite in employing not only rational thought but guesses, emotions and feelings to prospectively create personally preferred solutions to given problems. Complexity theory is mainly employed in retrospective analysis in order to find causes and relationships in complex phenomena such as in meteorology or in economics, while its predictive capabilities are rather limited. Complexity theory is constrained to probabilistic predictions based on general rather than specific cases. In complex architectural design projects, this contradiction is nothing new. Designers of all disciplines deal with uncertain and vague conditions and have to rely on science as well as guesses and human intuition to achieve results likely to work. As a result, design processes may be understood not as a rational 'thinking before acting', but a more human-centred 'feeling and thinking while acting' (see [17]).
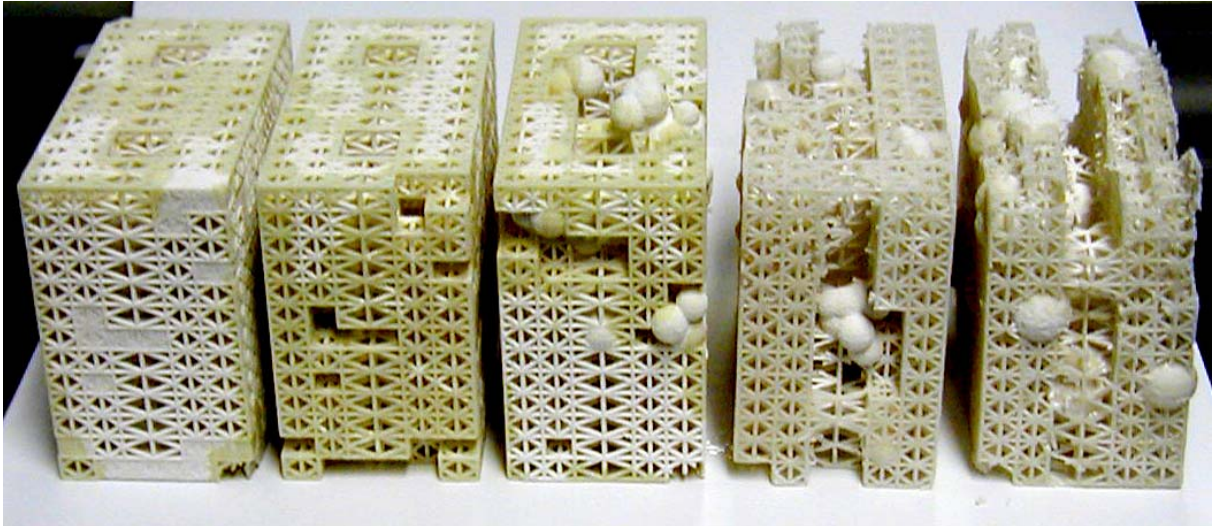
Figure 5: Generated grid structure at various stages of digital decay (rapid prototypes)

While architects are used to design for complex problems, the general method of dealing with complexity is to generalize and impose simplified structures onto complex contexts in top-down design processes. Design solutions produced in this way typically lack relationships and interfaces relating them back to their environments. Emergent natural order, on the contrary, derives its coherence entirely from large-scale contexts, but is not directed, since it develops without planning. The generated digital decay shown in figure 5 describes an additive and a simultaneous subtractive growth process, both progressively infesting a linear (modernist) grid structure. The state of a complex system is produced by sets of conditions and constraints, which are created by chance and may change over time. A fundamental dilemma between both notions of order emerges: How can architecture combine the richness and dynamics of emergent complex order with the economy and control of traditional top-down planning methods? And how can the application of emergent order in architecture meet the social responsibility of planners?

In addition to the question of control, complex phenomena have introduced the necessity of considering time in architectural design. Although movement has been an architectural topic for a century, it has been considered mainly in relation to building form and composition. Firmness and permanence have remained the dominant aims in architecture, and time has not been reflected in architectural design until recently (see for example [15]). While time and change are used in design processes today, this has not changed architects' belief in firmness and permanence. A further step into the understanding of complexity theory will enable architects to see buildings as dynamic elements in dynamic environments. Until today, architects have only seen activities within and around buildings as dynamic elements in architecture (see Tschumi, B.: Responding to the Questions of Complexity, in [3], pp. 82-87). Societies, economies and most aspects of daily life increasingly become connected and interdependent. Materials, appliances and inhabitants inside buildings behave in complex ways. Architecture, along with all other professions, will have to face these tendencies and find new solutions to the resulting open and dynamic problems. In this context, generative architectural design systems will have to develop into design as well as simulation tools, working with complex relationships of elements and simulating change over time.

4.2 Architectural Design and Metaphor

Design methodologies have to account for the risks arising out of a lack of predictability. To tackle this problem, architects traditionally rely on vague bodies of knowledge formed mostly through experience. This knowledge includes previous solutions to certain classes of architectural problems as well as personal methods to develop solutions for previously unknown problems. Since architectural design problems are unique, there is only very limited systematically accumulated and common methodology. To deal with and communicate about design problems, architectural design uses metaphors as guidelines. Metaphors can be used to describe situations in general, to describe intended design outcome and to serve as guidelines as well as ways of understanding. They can be shared and communicated, used to explain and still be interpreted individually. Well-known examples are the metaphors determining Modernism's understanding of architecture: 'open plan', used by Wright, or the famous 'houses as machines for living' as proclaimed by le Corbusier.

Metaphors arise from and convey a view of reality, influencing activity and ways of thinking in design response to reality - solving problems simply means representing them so as to make the solutions transparent [21]. Guiding metaphors, shared and communicated in architectural design contexts, change over time, reflecting general changes of (economic, social, or scientific) situations. Changes in the conceptions of role, power and functionality of architecture are usually accompanied by a rethinking and (re)invention of design metaphors (see [14]). Generative design tools also develop from design metaphors, reflecting perceptions of design problems as well as a paradigm's shortcomings.

4.3 Complexity Theory – a New Toolbox for Architectural Design?

As a scientific tool for analysis and description, the direct applicability of complexity theory as a new design method appears rather limited. Neither can it be used as a precise tool for prediction, nor does it provide immediate guidelines to design. Understood in a more fundamental way, though, design perspectives are changing due to the influence of complexity theory. Besides rather indirect changes to human viewpoints, however, generative architectural design may implement principles derived from complexity theory in more specific ways. Generative tools cannot predict the outcome of specific complex design projects, but they might well be useful in approaching or evaluating solutions by giving an impression of complex systems' properties when faced with changes in their environments. The modes of complexity mentioned by Rescher [20] suggest future directions and challenges to generative architectural design. Future generative architectural systems will have to facilitate elaborate hierarchies of elements and allow for a broad range of functional complexity properties involving change over time. Massively parallel modes of communication, interaction and feedback structures between design elements will be of particular importance.

Complexity theory shows that in all complex scenarios, long-term predictions are impossible: no scientific theory can yield certain predictions for unique design problems. As a possible reaction, architectural designers might focus more on the ability of their products to cope with challenges of an essentially dynamic and unpredictable future. Problems arising out of complex situations often have more than one possible outcome. Therefore, generative architectural design might consider designs that are relatively open or 'unfinished', so that architectural solutions are not determined by past predictions or guesses but by actual future events. These characteristics have been associated with 'living buildings', and envisioned by Frazer [9] as a future direction of generative evolutionary architecture.

By realizing the complex nature of architectural problems, architects will need to use new metaphors, expanding traditional paradigms in architecture to accommodate new concerns. These include unconventional hierarchies, energy and communication flows as well as elements with certain degrees of freedom to adapt to change. Central to a more flexible and adaptable architecture is the organisation of infrastructure and communication as dynamical elements that connect with and react to the environment. In this context, generative architectural design offers ways to handle complexity, but new approaches to work with and manage complex systems are required.

5. Conclusion

The introduction of complexity theory into architectural design has several motifs. Besides an interest in new aesthetics, architecture seeks coherence with social and scientific viewpoints. Complexity theory offers a new view on natural phenomena – including human activity – and encourages hopes for a more natural and humane quality in architecture. Rather than imposing over-generalized systems, architecture needs to acknowledge complex, interconnected and changing realities. In the context of complexity theory, the prevalent idea of stability in architecture needs to be reconsidered: in environments that change rapidly due to networked parallel activities, permanence will have to mean the ability to adapt to changes.

Complexity theory does not yield a specific methodology to design, but it can be used to understand and deal with problems arising out of complex design tasks. The unique and complex nature of architectural design problems limits predictability of a solution's success, but complexity theory may aid in estimating a solution's appropriateness in the context of a changing environment. In a complex world, the process of design is never finished – design products need to be able to communicate, adapt, exchange and communicate after the design process has ended. Since design processes will continue throughout the lifetime of a building, generative design tools and their products will have to merge to some extent.

A central challenge to architectural design emerging from complexity theory is the question of control: while traditional design processes use generalizing but directed top-down control, complex systems are driven by massively parallel, non-directed bottom-up mechanisms. In order to use complexity in architectural design, ways have to be found to integrate both modes of control as well as providing the necessary open communication protocols. Generative architectural design systems of the future will have to deal with new modes of control, massively parallel dynamics as well as a changed view of time and predictability.

6. Acknowledgements

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