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ON THE COMPLEXITY OF THE DESIGNER-ARTIFACT-USER SYSTEM

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Abstract

The science of engineering design has often been studied with the same scientific tools as other domain of interest in engineering, such as mechanics and thermodynamics. However, design presents a host of issues not present in other engineering domains, issues such as human creativity and decision-making, uncertainty, changing market conditions, and synthesis. Taken together, these and many more issues are evidence of the complex nature of design in general. This paper addresses this inherent complexity in design by applying concepts and tools from the relatively new science of complexity. The designer-artifact-user system is defined as the complex system of interest, and then this system is analyzed using ideas from complexity science. A number of unsolved issues in design, including several important trade-offs, are understood as parallel issues that have not yet been solved for any complex system. Further, several important insights into design are also gained from complexity science, including the idea of "designing on the edge of chaos," pursuing sub-optimal "satisficing" solutions, and strategies for matching time-scales within the designer-artifact-user system. Finally several open areas of future research into applying complexity science to design science are identified, including the development of methodological, as well as computational tools.

Key Words: Design, design theory, complexity, complexity science

1 Introduction

The study of the engineering design science has often been pursued according to the same scientific approach used to study the other engineering sciences: solid mechanics, fluid mechanics, thermodynamics, etc. However, there are many important differences between design and the hard engineering sciences. Design involves creativity, people, social interactions, a great deal of uncertainty, synthesis and decision-making as opposed to pure analysis, changing market conditions, and the whims of users, to name several of the difficult issues involved in design. Because of all these factors, and more, we assert that design is qualitatively more difficult to study than the hard sciences. It follows, therefore, and seems evident, that the scientific tools used to study the hard engineering sciences should not be sufficient or always appropriate to use in the scientific investigation of design.

Granted, many investigators have used tools from the social sciences in studying design. The purpose of this paper, however, is to apply a new set of tools to the investigation of design science, tools from the sciences of complexity. In short, we assert that the fundamental difference between design and other areas of interest in engineering is the inherent complexity associated with design, complexity that is not found in other engineering fields. Until recently, there have not been many tools developed to deal with complexity directly, but this situation is rapidly changing, with the emergence of the relatively new science of complexity. By studying complex systems from a variety of domains, the investigators of this science aim to understand complexity itself, including its fundamental causes, consequences, laws and behaviors. A review of important insights from the science of complexity is presented in Section 2.

Complicating matters somewhat is the fact that the term complexity already appears in several different contexts within engineering research, so the precise system that is complex in design needs to be defined. We introduce a lexicon of important terms in Section 3 to articulate what we consider to be *simple* versus *complicated*, versus *complex*. Then the complex system of interest is defined as the designer-artifact-user system, elaborated in Section 4. We proceed to show how the designer-artifact-user system is complex, by showing that the designer-artifact-user system exhibits known properties of complex systems.

Having thus established the complex system of interest in design, in Section 5 lessons from the science of complexity are applied to issues in design that stem from its complexity. In particular, several unsolved issues in design are compared with equivalent unsolved issues in complex adaptive systems in general, in order to better understand these issues in design. Then known results from the science of complexity are applied to help solve several existing problems in design science, which is an important contribution. Finally in Section 6 open research issues are discussed and in Section 7 we offer closing remarks.

2 The science of complexity

2.1 History and overview

The science of complexity has emerged in recent years as a response to the realization that many important phenomena across a wide range of scientific domains possess features that arise from the interaction of many small subsystems, from individuals and corporations in an economy to elementary particles in a large molecule. The key realizations behind this science are therefore three-fold, 1) that many interesting and unsolved problems in science are complex in nature, and not simple, 2) that problems across a wide range of domains have complexity in common, and 3) that complexity itself can be studied.

A leader in the study of complex systems, which was organized for the expressed purpose of understanding complexity, is the Santa Fe Institute in New Mexico, USA. Of the many publications from the Santa Fe Institute, the book *Complexity: Metaphors, Models, and Reality* (Cowan, Pines et al., 1994), is of particular interest because it presents a uniquely thorough, wide-ranging, and often technical treatment of a variety of views of complexity from leaders in the field, both in terms of what is known and what is left to be discovered. Our brief review of some important ideas in the science of complexity is thus drawn chiefly from this book. However, all of the individual authors cited below also have many other publications, including popular and technical books, journal and magazine articles, as well as conference papers, all available to the interested reader through the extensive lists of references in the book edited by Cowan et al.

The domain of interest to the science of complexity is predominately complexity's manifestation in complex systems. A complex system may loosely be defined (a formal definition is still a subject of debate) as a collection of a large group of strongly interacting parts exhibiting non-linear dynamical behavior. Complex systems may be further classified as either non-adaptive or adaptive.

2.2 Complex adaptive systems

The concept of a Complex Adaptive System (CAS) has been described rather informally as a system "with many different parts which, by a rather mysterious process of self-organization, become more ordered and more informed than systems which operate in approximate thermodynamic equilibrium with their surroundings." (Cowan, Pines et al., 1994, pg. 1). The physicist Murray Gell-Mann identifies the cycle in which all CAS seem to operate (Gell-Mann, 1994) as follows:

I. coarse graining of information from the real world
II. identification of perceived regularities
III. compression into a schema
IV. variation of schemata
V. use of the schema
VI. consequences in the real world exerting selection pressures that affect the competition among schemata

However, perhaps the most important property of a CAS (that distinguishes it from most of the systems with which engineers are accustomed) is that CAS are *open* systems. CAS are situated; they operate and interact within a larger environment wherein the CAS accepts energy in and exports energy out. Moreover, because the CAS is adaptive, some of the energy in is used to change the internal state of the CAS. Usually this flow of energy in and out is continuous; thus the CAS is continually in a state of flux, constantly adapting to what is usually a changing environment. Another important consequence of CAS being open systems is that the second law of thermodynamics, which is formulated expressly for closed systems, is not applicable. Thus in CAS we often see a *decrease* in entropy (increase in order) over time, sometimes seen as evolution.

2.3 Scale in complex systems

A common organizational structure of many complex systems is in the form of a hierarchy (cf. (Simon, 1996)). Often each level in a hierarchy is associated with a different time and / or space scale. For example, in the complex system of the early physical universe, near the very beginning of time, interactions occurred over time intervals of roughly 10^{-50} seconds; then after basic nuclear particles formed, interactions occurred in some 10^{-20} second spans, and later in chemical reactions, another level in the physical hierarchy, at the 10^{-12} second level, and so on (Cowan, Pines et al., 1994, pg. 3). Therefore in the analysis of complex systems, it is sometimes possible to assign system components to a particular hierarchy based upon observed time and / or space scales.

2.4 Criticality in complex systems

A final interesting feature of complex systems, both adaptive (such as organisms, economies, proteins, language, etc.) and non-adaptive (such as fluid turbulence, cellular automata, and avalanche models) is their *criticality*, which describes, usually in system specific terms, the behavior of the system on a scale ranging from quiescence to total chaos. At some point along this continuum, complex systems usually undergo a "phase transition" where the system goes from being well-behaved to unpredictable. Where the phase transition occurs is the critical point. Noted researchers in the field have argued that complex systems, adaptive or otherwise, tend to evolve toward and thus exhibit behavior near or at the critical point. The physicist Per Bak cites a number of important examples from physics, including the organization of the earth's crust and consequent earthquakes, fluid turbulence and generated vortices, forest fires, cloud formation, and solar flare activity (Bak, 1994).

3 Lexicon of complexity in engineering

Since the definition of complexity is still under some debate, it is important to define exactly what is meant by complexity and other related terms in the context of our discussion about design. However, since formal definitions are not widely agreed upon, we shall have to suffice with informal working definitions for the time being.

For our purposes, *complex* is used as an adjective to describe a class of systems each consisting of a (usually large) group of strongly interacting parts exhibiting non-linear dynamical behavior, for example the human brain, or the global economy. We shall use another term, *complicated*, also as an adjective, but to describe a class of systems that consist of a (usually large) group of weakly or moderately interacting parts that usually exhibit linear dynamic or static behavior, for example, an automobile or a tuning fork. Implicit in these definitions is the assumption that with increasing interaction between system parts comes non-linear behavior, which can readily be demonstrated, for example, using artificial neural networks. Finally we shall use the term *simple* as an adjective to describe a class of systems that consist of a (usually relatively small) group of weakly interacting or non-interacting parts that usually exhibiting linear dynamic or static behavior, for example, a two-bar linkage or a roller bearing.

While somewhat informal, these definitions agree with more advanced theoretical derivations of these terms, e.g., as done by Rosen (1991), who defines a simple system as one which can be modeled completely. A complex system, according to Rosen, is one that cannot be modeled completely due to impredicativities, i.e., self-referential causal loops that defy largest models. In this sense, number theory, as demonstrated by Gödel's famous incompleteness theorem, is complex in this sense, while any formalization of it, which is necessarily incomplete, is simple. The difference between what is simple and what is complicated in this view is simply a matter of the modeling effort involved.

Meanwhile, the term "complexity" is not new to the engineering field. Indeed, it has been applied in a variety of contexts. A recent review of the use of the term in engineering design is presented by Summers and Shah (2003), who discuss the complexity of the design solution, i.e., the artifact, the design problem alone, and the solution procedure used to solve the design problem. Summers and Shah focus on the complexity of the solution procedure as a means of measuring design complexity. Measures for the design solution and the design problem also exist, e.g., by measuring number of parts in the case of artifacts, or number of design variables and constraints in the case of design problems. However, to apply the ideas from the science of complexity reviewed in the previous section, we believe that it is not appropriate to study the artifact, the problem, and/or the solution method in isolation, for much of the complexity design involves the connections between each of these domains.

4 The designer-artifact-user complex system

4.1 Formulation of the designer-artifact-user complex system

One of the strengths of the science of complexity is its ability to handle very large and very complex systems. Thus it frees the investigator from the self-defeating need to over-simplify the problem under study. To study complexity in design, therefore, we need not focus on just artifacts, or just problems, or just solution procedures, as has been done in the past. There is in fact total freedom to define the complex system of interest, the "design system," as it were, to encompass all relevant issues and stakeholders. However, in every design there will be different issues and stakeholders at play, but incumbent to every design are at least three major subsystems: 1) the designer(s) of the artifact, 2) the artifact(s) being designed, and 3) the user(s) of the artifact. Thus we propose that the complex system of interest in design is the designer-artifact-user (DAU) system.

4.2 The environment of DAU systems

The properties of the designer-artifact-user system involve many important aspects of design not stated directly in the three component subsystems. First, as in every system, the DAU system is situated in a larger environment. However, the specific environment in which a particular DAU system is situated depends upon the specific design. For example, in the case of the design of a family of consumer appliances, the environment would consists of a corporation, local, regional, national, and global economies, legal regulations, competitor corporations and products, the physical world, etc. Each of these elements of the environment would act upon the DAU system in different ways, in terms of inputs and outputs to and from the DAU system. A generic situation of this kind is shown in Figure 2.

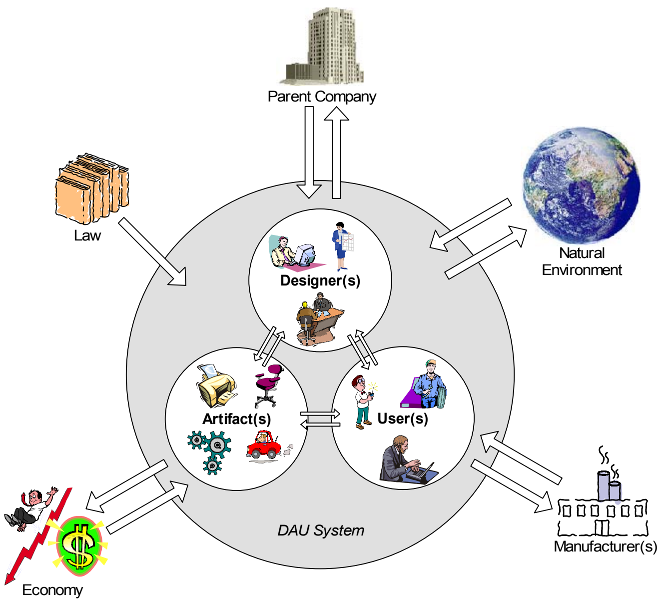

Figure 2. Generic situated designer-artifact-user (DAU) system

4.3 Multiplicity in DAU systems

Each of the three basic subsystems within a DAU system need not be singular. There may be multiple designers, artifacts, and/or users. By considering the general case of multiple designers, we open the door for important insights into concurrent engineering and collaborative design, two recent and important topics of design research. By considering the general case of multiple artifacts, we open the door for important insights into product family design, another hot topic of design research. And by considering the general case of multiple users, we can consider not just the end user but anyone who might interact with the artifact throughout its life-cycle, thus opening the door for important insights into areas such as human factors, mass customization, design-for-manufacture / maintenance / serviceability / recycling, etc. Moreover, by considering designer(s), artifact(s), and user(s) together in the same system, we can also study the interactions between each of these subsystems, and perhaps most importantly, the system behaviors that result from those interactions.

4.4 DAU systems as complex adaptive systems

It would be difficult to argue that DAU systems are complex adaptive systems (CAS) merely by a straight application of the definition of CAS, because there is no formal accepted definition of CAS. However, there are widely recognized and studied properties of CAS. Thus we can show that DAU systems are CAS by showing that the properties of a DAU system are consistent with those of a CAS, in particular the quintessential CAS cycle as identified by Gell-Mann (see Section 2.2), as follows:

Coarse graining of information from the real world:

In a DAU system, coarse graining occurs in the problem definition stage of design. Here the designer's goal is to understand the problem at hand. This must be done by a process of "coarse graining," in other words a process of sampling, surveying, and gleaning information about the design problem from wherever possible in the real world. This may take the form of a formal problem statement from management, user surveys, the designer's own experience, marketing information, legal and cost constraints, etc.

Identification of perceived regularities:

In a DAU system, the identification of regularities occurs as designers further refine their understanding of the design problem by sorting out the initial data gathered in the coarse graining phase, which is often contradictory and/or incomplete. Often designers will organize the design problem in terms of requirements with associated constraints, criteria, and goals, which may or may not be articulated in some form such as a Requirements List (see, e.g., (Pahl and Beitz, 1996)).

Compression into schema:

After designers sufficiently understand the problem to continue design work, the broad design space available to the designers must be narrowed in order to arrive at solution concepts. Thus the CAS compression phase is equivalent to the conceptual design phase in a DAU system (where the terms "schema" and "artifact concepts" essentially become interchangeable). This involves exploration of the design space using ideation techniques as well as combination and selection of concepts. The resulting schema is thus a full system solution concept, possibly accompanied by some sort of prototype, physical or otherwise.

Variation of schemata:

Once an initial system concept is found, the designer must improve, test, and refine that concept in order to arrive at a final production worthy artifact. Often this process requires extensive iteration of earlier phases of the design process. In other cases, the entire design project may be an exercise in variant design, where an artifact already exists, but the object is to modify it to suit new circumstances. These design activities within a DAU system are thus equivalent to the variation of schemata phase in the CAS cycle.

Use of the schema:

In a DAU system, the schema is used when the artifact is released on the market as a finished product. In the discussion above, the manufacturer, since it is not explicitly defined to be a member of the DAU system, exists and interacts with the DAU system from the DAU system's external environment. Clearly those interactions are important, but perhaps no more or less important than other interactions from the environment, such as from competitors, bodies of law, environmentally conscious issues, etc. In other cases, such as in one-off products and software, there may be no significant manufacturer at all. At any rate, the schema may be used by a variety of users described by the DAU system's user subsystem, including people involved in any manufacturing process necessary, end users, maintenance and service personnel, etc.

Selection pressures that affect the competition among schemata:

In a DAU system, selection pressure is exerted from the outside environment. This pressure may come from the economy and changing user whims, which would feedback into the DAU system affecting choices and ideas for variant designs. This is especially important for product family design, in particular for what we have termed in other work as "evolving product families" (Maier and Fadel, 2001). Different selection pressures may come to bear in an original design exercise, where for instance corporate management or marketing people may influence the designer's decisions. It is important in this context not to confuse the competition of competing products in the marketplace—which occurs within a different CAS, the economy (cf. (Arthur, Durlauf et al., 1997))—with the subset of competition in the economy that actually feeds back into the DAU system, which is all that is applicable here.

5 Lessons from the science of complexity

5.1 What is still unsolved

We may take some comfort from the fact that many of the long-standing problems in design coincide with equivalent problems in CAS in general. This suggests that our lack of understanding in these areas is not due to any particular lack of knowledge in the design field, but rather the difficult and complex nature of these problems in general. A list of outstanding problems that are common to both design (i.e., the DAU complex system) and CAS in general, organized by phases of the generic CAS cycle is as follows. This list is based upon the list of issues in CAS research deserving further investigation (of which the following is only a subset), as presented by Gell-Mann (Gell-Mann, 1994):

Coarse graining of information from the real world:

1. In CAS: The trade-off between coarseness for manageability of information and fineness for a better picture of the environment.
   In design: The trade-off between spending a lot time trying to understand the problem, i.e., by extensive user surveys, vs. spending less time in this phase although sacrificing understanding of the problem, in order to rush to market for a potential pay-off there.

Identification of perceived regularities:

2. In CAS: The tendency of a CAS to err by mistaking regularity for randomness and vice versa.
   In design: The problem of identifying true user needs vs. latent user needs vs. times when the user says they want one thing when in reality they actually buy something else. In other words, the difficulty of interpreting user data and other data that describes the problem, which is often incomplete and contradictory.

Compression into schema:

3. In CAS: The importance of continual evolution of the observed system with the difficulty inherent in estimating the probability of future histories.
   In design: Since the marketplace is continually changing, designers must confront the fact that by the time they finish designing the artifact, user preferences and other environmental effects such as market conditions may have changed.

4. In CAS: Trade-off between degree of compression versus time and amount of computation involved.
   In design: Trade-off between increasing the number of promising solution concepts and prototypes elaborated, versus time and money spent on them in development.

Variation of schemata:

5. In CAS: Variation usually proceeds step by step from what is already available, so how can schema change by large jumps?
   In design: Most products evolving slowly over time, with modest success. But occasionally a major innovation occurs seemingly out of no-where. How do innovations like this occur, and how can they be engineered intentionally?

Use of the schema:

6. In CAS: Method of incorporating largely random new data.
   In design: Designing for the real world: the artifact, once introduced, is subject to all the vagaries of real users and the real marketplace, whereas in order for the designers to design the artifact at all, most of this complexity was lost in the coarse graining phase.

Selection pressures that affect the competition among schemata:

7. In CAS: Fitness is an elusive concept
   In design: How can designers "optimize" a design to perform in an environment that is ill defined and approximate (out of the coarse graining phase) and ever changing? What is an appropriate fitness function?
8. In CAS: when maladapted schemata occur because of mismatched time scales
   In design: when products fail because the market changes faster than products can be designed or redesigned.

5.2 Useful results for design

5.2.1 Designing on the edge of chaos

An important insight into complex systems, as mentioned in Section 2, is their tendency to operate near some kind of critical point, sometimes referred to whimsically as the "edge of chaos." This is where living organisms seem to maintain themselves, where the most interesting cellular automata and game-of-life patterns emerge, and where physical models such as of avalanches operate as well. This suggests that this is where the DAU system either will or ought to operate as well. This supports the type of design that companies such as Ideo have recently been advocating (cf. (Kelly, 2001)), involving encouraging wild ideas and out-of-the-box thinking, a very flat organizational structure, and heavy emphasis on prototyping. The essence of this approach lies in its flexibility, a deep understanding of problems and opportunities, and the tremendous amount of ideas generated. The history of Ideo shows that this approach works. The operating on the "edge of chaos" idea helps us understand why. This may be contrasted with other schools of thought in design, which tend to focus on rigorous formal methods that usually assume one designer designing one product at a time.

5.2.2 Satisficing versus optimizing in design

In 1969, the economist H.A. Simon introduced the notion of satisficing solutions in design to describe solutions that were "good enough" if not the "best" in any strict sense (Simon, 1996). The lack of well-defined fitness for CAS in general supports the notion that satisficing solutions are indeed appropriate in design. Besides the pioneering work done by Simon using the decision theory that he developed, little attention has been paid to the notion of satisficing solutions, with a few exceptions (e.g., (Mistree, Hughes et al., 1993)). Rather, the vast majority of work has been on rigorous mathematical optimization. Complexity theory suggests that the former approach of finding satisficing solutions deserves more attention since it is more appropriate to the complex nature of design.

5.2.3 Time scale in DAU systems

In a DAU system, several different time scales are evident. First there is the time it takes for designers to design an artifact. Then there is the time the artifact is used by users (before being retired). There is also the time between improvements of the artifact by the designers. Problems can occur, as in other systems, when time scales are mismatched. As noted in Section 5.1, such a problem can occur in a DAU system when designers take too long to design an artifact, during which time the market may have changed to the extent that the artifact cannot be a success. A similar problem can occur when the cycle time of artifact improvements is either too long (i.e., letting a product become obsolete) or too short, wasting improvement costs on an artifact that would stay competitive. Complexity theory thus suggests that time scales within a DAU system must be compatible, *which can be intentionally engineered into the system*. The most difficult to control time scale is probably the one over which users use the artifact, however in some cases this can be controlled, such as by the level of durability of a physical artifact, or in some cases as an out-right expiration date, as in a software license. The time over which designers design an artifact can be modified by various means, such as by increasing the number of designers and / or their budget. The frequency with which artifact improvements are introduced can also be controlled.

5.2.4 Design as a complex phenomenon

In a broader sense, the discovery that the designer-artifact-user system is complex in the sense of other complex (adaptive) systems, validates a scientific approach to design as a science of complexity. This approach differs from other approaches to design as a hard science, or a soft science, or as empirical in nature. To be sure, design includes elements of each, but to neglect its complexity is to leave out something quite fundamental.

6 Open research issues

The list of open unsolved problems with both design and CAS in general obviously serves as a short list of issues worth tackling in the future. However, in order to address these issues meaningfully, investigations must be done with the knowledge that what is actually being investigated are complex phenomena. The starting point in any such research would be the open issues in CAS in general, and not necessarily those particular to applied design.

Another avenue of research is the application of complexity science the methodology of design. It seems logical that the process of doing design cannot be separated from the complex nature of design in general, as discussed in this paper. When coupled with an understanding of the complex nature of human thought, perception, creativity, and decision making, we believe there is much room for progress in our understanding of the scientific principles of how design ought to be done.

A third area of research is the integration of complexity science into computer aided design tools, which traditionally help designers deal with complicated systems very well, but do not offer much assistance with complexity. However, development in this area may have to wait for our theoretical understanding of complexity in design to become more mature.

7 Closing remarks

In this paper we have laid the groundwork for studying complexity in design using concepts and tools from the newly developing science of complexity. While most of the insights provided in this paper have been theoretical in nature, we believe this is an important first step for integrating the fragmentary approaches to design of the past, and paving the way for novel insights into the complex heart of design in the future. We would encourage interested parties from across the design community also to pursue this endeavor.

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