Complexity models in design

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1. Introduction

Complexity is a widely used term; it has many formal and informal meanings. Several formal models of complexity can be applied to designs and design processes. The aim of the paper is to examine the relation between complexity and design. This argument runs in two ways. First designing provides insights into how to respond to complex systems – how to manage, plan and control them. Second, the overwhelming complexity of many design projects lead us to examine how better understanding of complexity science can lead to improved designs and processes. This is the focus of this paper. We start with an outline of some observations on where complexity arises in design, followed by a brief discussion of the development of scientific and formal conceptions of complexity. We indicate how these can help in understanding design processes and improving designs.

2. Complexity in design

Many engineering designers consider several areas of their work as complex (Figure 1). First, the product, service or system under construction may be complex in its own right, both in structure and behaviour in use. Second the process of designing may contain many interrelated tasks, each having many subtasks. Third, the organisation of designers in project teams integrates complex sets of capabilities and experience. Fourthly, users, and those more widely affected through life cycle effects such as environmental impacts, provide a complex context for designs.

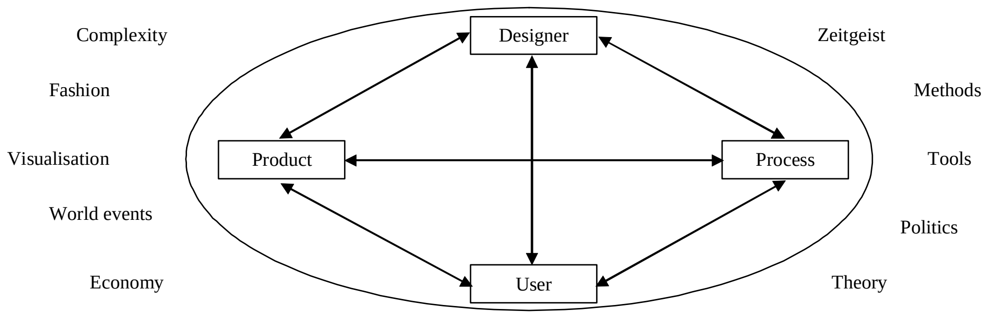

Figure 1 Designing in Context

The relation between product and process is a source of complexity. For example scheduling the product across available design resources and capabilities which make up the process is a difficult task, not least because individual design activities in the process have uncertain durations. The way that a product 'flows' across the resources and capabilities in the design process, with associated interactions between parts of the process is complex. Managing these flows is a challenging task. Designing in the informal senses described above has characteristics which are mirrored by established formal models and ideas in the theory of complexity (Nicolis & Prigogine 1989 for a physical science view, Suh, 1999 for a design view). Further, the way that designing develops intention, through concept to final design (Cross, 2000), appears to be an exemplar of how to model a complex system by increasing detail in representations through a process of iterative evaluation.

In 1961 Edward Lorenz, investigating the weather using a set of three equations that now bear his name observed that trajectories changed, even though they had the ‘same’ initial conditions. These chaotic systems, like the weather are very sensitive to the initial conditions, while the system remains bounded. Many designed systems have chaotic properties like this, from road traffic systems to aeroplane engines and perform best ‘on the edge of chaos’. Indeed the design process itself can be chaotic. Synthetic or designed systems follow patterns or laws which are not just consequences of natural science. *The Sciences of the Artificial* as proposed by Herbert Simon (1969) characterised design (and complexity) by rules and goals, hierarchies and decompositions. Computer simulation can generate considerable variety in these artificial systems from simple rules - cellular automata (Wolfram, 1994) and fractals (Mandelbrot 1983) are well established examples with numerous applications.

3. Structure and uncertainty

A helicopter rotor blade is complex not only in its form and manufacture but also in its function. Its design process is complex to the extent that it eludes conventional process modelling, with a large number of closely interdependent and related shape and material parameters which are determined iteratively (Clarkson and Hamilton 2000). Off road diesel engine designs are customised for users and subject to environmental impact legislation. The main complexity lies in the interactions between product and users (and the logistical effort involved in designing and producing thousands of slightly different products). Power generation switchgear is a customisation of a standard product completed on a contract basis. Managing several different products through the design and manufacture process are complex scheduling problems under uncertainty (Earl et al 2001).

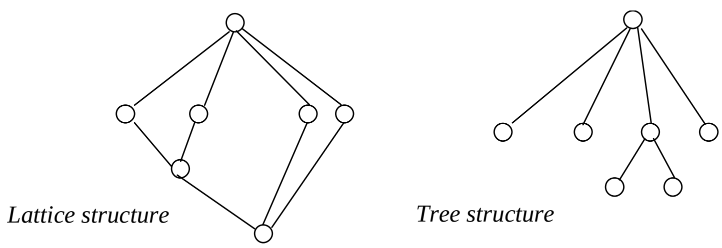

Figure 2 Tree and lattice structure

A design may be structurally complex - an engine has many parts and specific functional relations among parts. Parts and relations between parts form a hierarchical structure which is not necessarily a tree-like structure but may display more connected lattice properties (Figure 2). For example a control system might be shared by several electromechanical subsystems in a product. Likewise the design process may be complex in structure with many subtasks and relations or many iterative cycles each with inherent uncertainty.

The structure of a design is dynamic, changing through the process as details are specified and performance analysed. However, during the design process it is not only the structures of parts which change but also performance and behaviour of successive design proposals. Analysis at each stage in product development assesses performance or potential performance against specification. Mismatch can occur either in detail or type of behaviour. Mismatches in details are handled iteratively whilst mismatches in type resulting from new behaviours emerging during the design process are more difficult to control. Exceptionally these new behaviours may be desirable - the delightful serendipity of design - but for the most part engineering designers try to eliminate them. The later stages of many design processes try to eradicate these unwanted behaviours, such as vibration, noise, ESI, rumble, heat, etc. The design process converges to a final design in which behaviour is predictable and desirable with lower complexity especially in the relation between product and user. Another source of complexity is the interaction of product and process. Complexity arises from the way products form a 'traffic' through the network of activities and tasks in the design process.

At the beginning of a design process designers are uncertain about the details of configuration and parameters, but may have a detailed functional specification. Uncertainty is present in all areas of design and designing (products, processes, users, and organisations). New designs have parameters and behaviours which are not known completely beforehand, processes have uncertain durations and uncertain effects, users and conditions of use can change, organisations change and more widely contexts, environments and long term conditions of use are unpredictable. All these uncertainties make planning design processes harder by increasing the numbers and combinations of possible outcomes. Some have argued that uncertainty is at the core of design complexity (Suh, 1999).We will discriminate two basic types of uncertainty; 'unknown' and 'known' uncertainty. These types are present in two areas (i) descriptions and (ii) data (which includes uncertainty in measurement). We can also discriminate types of order; structural order of relations between parts, dynamic order of patterns of behaviour and the order imposed by constraints and natural laws. Generally, complexity seems to occur when there are high levels of uncertainty combined with high levels of order. 'Known' uncertainty is based on variability in past cases. It can be characterised by probability distributions (for example of process task durations) or probabilities of a process (such as a computational analysis or prototype test) improving design performance. Known uncertainties put limits on possibilities and associate likelihoods with them through probability distributions. In other cases uncertainties may be known but their effects are unknown uncertainties in behaviour. The uncertainty of surprise is an 'unknown' uncertainty in the sense that there is no particular expectation of such an event. Internal unknown uncertainties arise in the product, the process, the user or the organisation itself. External unknown uncertainties come from the context in which the product or process operate.

Uncertainty in data, not just in its accuracy but also in its completeness and consistency, is a major factor in design processes and product development. As designs are developed; from concept to layout, and then to manufacture, many types of data are generated. Incompleteness is a characteristic of data during design, especially with speculative proposals. In some complex human systems it is impossible to have data that are complete or consistent, and the science of these systems has to accept this as one of its axioms. It is not simply a case of collecting better data to eliminate inconsistency but to provide robust predictions even though the data are incomplete and inconsistent. Further, here are underlying 'unknown' uncertainties in all measurements. In chaotic systems, the unpredictable response to 'unmeasurable' differences in initial conditions is an unknown uncertainty.

4. Complex behaviour: dynamics, connectivity and information

The dynamics of complex systems may be deterministically chaotic in that the slightest errors in measuring the initial conditions change behaviour significantly but within bounds. Examples include many human and socio-technical systems. Designing and its processes are an example of such hard-to-predict systems. And many products themselves display these characteristics of uncertain behaviour especially in the context of the wide spectrum of 'users' from the immediate customer to those affected during the design life cycle and beyond. Gateway processes in companies force products and processes to reach certain well defined points. This is a cyclic process of description and prediction. Suh (1999) advocates this as a design principle for time dependent systems such as design processes and schedules. He advocates attempting to transform time dependent combinatorial complexity (with increasing uncertainties into the future and their 'knock on' effects) into periodic complexity (with uncertainties being reset at regular intervals). This is achieved by introducing gateways or reducing the dependencies between parts of the design process. Modelling the dynamics of complex systems requires an appropriate notion of time. There is an interplay between 'clock' time, and 'system time' defined by the structural 'events' of the system. Mis-matches between system time and calendar time are well known, especially in the software industry. Understanding the complex interplay between events and time is fundamental in design, planning and management.

Flows of energy, information and matter, require *connectivity* among parts. There is a conflict between facilitating essential communication and decoupling parts of the system to eliminate undesirable interference and noise (as for example in reducing the options offered on a car). Designing an infrastructure 'backcloth' to carry the system 'traffic' is an essential part of applied complexity theory in planning and management (Johnson, 1995). Flows take place on networks of connectivities. In design several types of network may be present:

• product components are connected by function, geometry, manufacture and assembly;
• people such as engineers, analysts and designers are connected in team structures, hierarchies and even friendship;
• activities and tasks in the design process are connected by information and design representations, with process interfaces which may operate with checks or as gateways;
• a range of products in a company are connected by shared components, methods of manufacture, designers or design capabilities; and
• supply networks include both designing, manufacturing and service outsourcing.

Networks can change rapidly over the course of a design project. One of these is the network of connectivities among the relevant knowledge of the participants. As the project proceeds the connectivities will change as knowledge is acquired, analysed and embodied in a design. Other networks such as the structure of teams change more slowly, during a project. Although connectivities may be present they may not be continuously active but activated by events such as a competitor's new product or a scheduled project meeting. One of the main challenges of design management is to keep an overview of these multiple connections through which information needs to flow, change and propagate (Jarratt et al, 2004).

Many complex systems have large numbers of interacting heterogeneous elements. Computational search of very large spaces of possible configurations of connected elements is thus an important tool in design. As most search spaces are large and exhaustive search is not feasible. Heuristics or random search techniques such as simulated annealing or evolutionary algorithms are used. Simulations are a vital tool to evaluate dynamics of possible configurations of connected elements encountered during search.

One measure of the complexity of existing systems is how extensive its description needs to be to capture the features of the design or its behaviour. Algorithmic information theory (Chaitin, 1987) provides the basis for comparing such descriptions. The idea is that designs with compact descriptions, in terms of shorter procedures or fewer rules to generate them, have lower complexity. Designs exhibiting order and regularity in their behaviour may have short descriptions whilst uncertain and unpredictable behaviour may require longer descriptions. However, taking this to an extreme, if behaviour is random then descriptions again become short as there is little information in the description. Applying information complexity to the design process is problematic because statistics on uncertainties have little significance since the characteristics of the process depend on the particular product being designed, the resources available and the 'memory' of similar products.

5. Complex Design -examples

The compressors of jet engines use combinations of static and rotating blades to drive air into the combustion chamber. As the blades attached to the rotor pass the fixed stator blades, there is a pressure gain. By changing the geometry of the blade the pressure can be increased, but eventually the compressor becomes unstable, with small changes in the control variables causing large and sometimes undesirable changes in pressure. Engineers currently design engines to run ‘on the edge of chaos’, pushing the parameters to increase performance while (safely) keeping the system out of the dangerous chaotic region. Traditionally the blades were fixed, but some engines have mechanisms to set the angle of the blades more optimally for take-off as well as cruising. Current research is investigating the possibility of designing the blades to self-organise, with each blade acting as an agent, selecting its own optimal settings throughout operation of the engine. Related research in complexity science and intelligent systems is reported in Johnson and Irvani (2004).

The structure and dynamics of processes are key to understanding the behaviour of manufacturing as a complex system. Uncertainties and variability in manufacturing processes can to some extent be controlled. By measuring manufacturing system behaviour quantitatively in terms of flows, lead times, inventories and queue size, an information theoretic complexity can be assessed. Highly predictable processes will have low complexity (as do highly variable processes). The literature on manufacturing system complexity (Frizelle and Suhov, 2001) describes information measures of overall order in systems with high levels of local uncertainty. This uncertainty is ‘known’ because processes are repeated often and statistics can be constructed. However, we note that in design local uncertainty is hard to quantify, processes can change and are susceptible to a wide range of external disturbances. A distinction made in manufacturing systems between static and dynamic complexity is also applicable in design

Aerospace engineering provides illustrative examples of design complexity. For complexity arising from the interaction of product and process consider the functional and modular groupings in a jet engine. The compressor and turbine are commonly designed by separate teams. The combination of the effects of design decisions made rationally by individual domain experts are only apparent at prototype test. On the one hand decoupling of processes has reduced complexity in designing but on the other has increased complexity in the product and its behaviour, introducing unexpected ‘emergent’ behaviour. Undesirable emergent behaviour is subsequently removed from the design. Emergent behaviour arises continuously as a design proceeds from concept to embodiment and manufacture. In some cases this emergence represents new discovery and inspiration for design innovations whilst in other domains such as engineering the process of design is to iteratively remove undesirable emergent behaviours. The final design has, in system dynamic and information senses, minimal complexity. The description of the possible behaviour of a ‘well behaved’ design is simple.

Designers generally avoid emergent behaviour which is random and chaotic by locating designs within margins. Optimal or high performing designs operate close to margins where behaviour becomes very unpredictable or chaotic. Several complexity problems occur here. First, unexpected interactions between parts may cause behaviour to pass over the margin. Second, it may be that reductions in design process complexity through modularity give this higher design complexity in behaviour. Third, a design has a parameter envelope in which the design performs predictably, but optimal performance often occurs in the margins of this envelope. Operating in the margins, means that behaviour is complex and users require assistance to reduce complexity. An historical example is the comparison of turning performance of Spitfire and Messerschmitt Me109. Theoretically Spitfires had better performance in a wider envelope but Me109’s could be flown in narrower margins of their narrower envelope because they incorporated a passive moving element in the wings’ leading edge. Although giving only a small aerodynamic improvement these elements signalled to the pilot that the margin was being encountered. Inexperienced pilots could therefore avoid unstable behaviour, reducing complexity and improving performance.

6. Conclusions

In this paper we have shown that design can possess complexity in (a) products, (b) processes, (c) users and (d) management or organisation. Although each of these elements can be complex, it is their combination that can cause the high levels of complexity that makes the design process hard to understand and control. This complexity can be conceptualised and described through a number of formal approaches that give insight into the behaviour of designs and design processes. However, there is no unified theory of complexity and no single theory captures all aspects of a complex system.

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