

JS Gero and ML Maher (eds) (2005).
Computational and Cognitive Models of Creative Design VI,
Key Centre of Design Computing and Cognition, University of Sydney, Australia pp 19-44

SOCIAL MODELS OF CREATIVITY

Integrating the DIFI and FBS frameworks to study creative design

RICARDO SOSA

Instituto Tecnológico de Estudios Superiores de Monterrey, Mexico

and

JOHN S GERO

University of Sydney, Australia

Abstract. This paper presents a framework for experimentation about design as a social activity. It accounts for the complementarity of generative and evaluative processes by individuals and groups and is used to inspect phenomena associated with creativity in the interaction between designers and their societies. The results illustrate ways in which the role of designers as change agents of their societies can be largely determined by how evaluating groups self-organise over time. An implication is that the isolated characteristics of designers may be insufficient to formulate conclusions about the nature and effects of their behaviour. Instead, causality could be attributed to situational factors that define the relationship between designers and their evaluators.

1. Introduction

The study of creativity tends to concentrate on individual processes. Conventional creativity research has aimed at explaining the characteristics that distinguish a person, a product, or a generative process as creative. The often implicit assumption in the field is that creativity can be explained in terms of internal mechanisms or qualities that a few special individuals possess, and others lack. However, well-known concepts such as historical or H-creativity (Boden 1994; Sternberg 1999) and big-C creativity (Gardner 1993) have acknowledged social evaluation as central in the definition of creativity. Namely, creativity has been defined as “the generation of ideas that are both novel and valuable ... and values are negotiated by social groups” (Sternberg 1999). A key question is therefore: How can we understand creative design based on the study of an independent generator

(in laboratories or computational models) in isolation, leaving outside interaction with the social level?

Communication between studies of generative and evaluative phenomena seems necessary to understand creativity as the product of the interaction between individual and social behaviours (Csikszentmihalyi 1988). To enable the study of the social nature of creativity in design, we have developed computational social simulations in recent years (Sosa 2005; Sosa and Gero 2002, 2003a, 2003c, 2004a, 2004c). This paper summarises some of the key aspects of our frameworks, their potential contributions, and a number of important insights based on this work.

2. Framework

This section introduces an experimental framework for the study of social aspects of creativity in design. The aim is to capture principles of behaviour and interaction in complex systems, which could help understand the dialectical relation of design and society.

2.1. CELLULAR AUTOMATA (CA)

In previous studies we have presented CA models to study the role of design in triggering social change (Sosa and Gero 2003b). These studies extend the canonical modelling of social influence used to explain the diffusion of values and the persistence of diversity in a social group. In such CA models, large groups or populations exhibit emergent coordination based on a set of simple rules of decentralised behaviour that instructs a large number of individuals to exchange values at the local level as a function of compatibility with their neighbours (Axelrod 1997).

Extensions that we have carried on these models include CA where a minority of individuals in the population is able to introduce new values instead of only exchanging existing values with their neighbours. The effects of this behaviour of ‘dissent’ over long periods of time provides a number of insights regarding the potential of design to trigger social change (Gero 2000). A new value originated by an individual or a minority may be first adopted by adjacent contacts, and it may continue to spread across the greater social group until it becomes dominant in a population. New subsequent values may be introduced and they may be adopted by all or a large majority of individuals in a group creating a cycle of ‘creative destruction’ (Schumpeter and Clemence 1989). The likelihood of any given value introduced is determined in a CA of this type by a number of factors. Firstly, our results have shown that individual dissent can remain at low levels and still be able to trigger cycles of collective change. Only if a majority of individuals interacting at the local level follow a convergent behaviour, can a value be spread and become dominant (Sosa and Gero

2002). In other words, a majority of imitators coupled with a minority of dissenters, is necessary and sufficient to support group formation or ‘cultural emergence’ (Axelrod 1997), as well as periodic transformations or ‘revolutions’ (Kuhn 1974) in these types of decentralised, self-organising, complex social systems.

We have also used CA models to show that the role and impact of a minority is importantly determined by different types of factors that are not always obvious. For instance, keeping the individual rules of behaviour unchanged, we have shown that by varying the ‘degree of separation’ in a social group, one can control the resulting emergent patterns of diffusion and group transformation. The higher the distance between neighbours of adjacent individuals, the higher the likelihood of sustaining diversity in a group. Consequently, in same-size social groups where acquaintances are less likely to be shared between individuals, novel ideas are more likely to be shared by groups and more alternative ideas may become dominant for shorter periods of time. In contrast, in same-size groups where acquaintances are largely the same between individuals, a novel idea is less likely to be spread, but once it does it will show more ‘cultural resilience’ (Sosa and Gero 2003b). The key implication is that in self-organising systems the probability of a design artefact of being adopted and of maintaining the preference of a society can be a function of social factors, which sit outside the artefact’s properties.

Lastly, we have also used CA models to illustrate a fundamental social principle: non-linear causality of change. In decentralised systems where chaotic phase transitions can occur, individual properties of change agents are not strong determinants of group change (Sosa and Gero 2003a). Non-linearity refers to the observation that individuals or minorities may trigger an equivalent number of types of change episodes in their societies, even if their individual potential of dissent differs significantly. The first reason for this apparent paradox is that certain social conditions may be necessary for dissent behaviour to emerge in the first place; i.e., disagreement is only possible as a response to some convergent state of neighbours, which lies outside the control of the change agent. Secondly, social conditions may also be necessary for dissent behaviour to have an effect at the collective level; i.e., the success of novel ideas depends on the behaviour of others. For these reasons, it would be inaccurate to infer or attribute any special characteristic to individuals that trigger group changes in CA-like systems. The latter show that episodes of social change depend on a timely combination of individual and social processes.

The types of insights extracted from manipulating CA models are of interest because they enable analysis of interaction patterns in complex systems. However, the principles that one can formulate based on this type of evidence are too general to contribute towards a theory of creativity in

design. Namely, CA models can be applied to many different systems including insect colonies, magnetic particles, and chemical structures (Wolfram 1986). The underlying characteristics of these social, biological, and physical systems is their ergodicity: the tendency to converge from any given initial state (Liggett 1985). This has been shown to be a product of recurrent randomness, which characterises one and two-dimensional modelling spaces like those usually used in CA representations (Wolfram 2002). However, no evidence exists to support the idea that social systems are one or two-dimensional, human societies are often described as multi-dimensional systems when represented by social networks. In such types of systems, transient random walks cause non-ergodicity, i.e. maintenance of diversity. CA have been shown to illustrate a number of ways in which design can be seen as a source of cultural diversity (Sosa and Gero 2002).

Nonetheless, the over-simplification inherent to CA models, equips them with little explanatory power. How, when and why change is triggered in CA societies, are all questions ultimately answered by their stochastic nature. All emergent group dynamics occur ‘because of randomness’. To attempt anything else, one needs a degree of causality based on an idea of agency.

2.2. MULTI-AGENT BASED SIMULATION (MABS)

Social ability in multi-agent systems is still poorly understood. In the canonical multi-agent system, behaviour is described at the individual level with no explicit representation of collective structures (Wooldridge 2002). In such systems, the agent-environment divide conflates the social and the physical states of the system. Insects and particles may be veridically modelled in such way where sociality is construed by the observer outside the system. However, in human agency second-order emergence is necessary to support awareness of others (Conte et al. 2001).

To develop a multi-agent based simulation (MABS) of design, we adopt the basic units of a social system of design drawn from the Domain-Individual-Field Interaction (DIFI) map of creativity (Feldman et al. 1994). This framework can be used to locate creativity in the interrelations of three main parts of a design system: domain, field and individual designer. The domain consists of the set of shared knowledge, beliefs, techniques, and evaluation criteria shared by the members of a given community. Fields include groups of individuals who share a common domain. The key implication of the DIFI framework is that creativity is not reduced to the characteristics of individual designers, products, or processes. Instead, situated in a dynamic environment and in relation to external factors, creative designers generate ‘the right product at the right place and at the right time’ (Simonton 2000) where ‘rightness’ is largely defined by the society.

To specify the behaviours of DIFI components in a computational social model of design, we apply the FBS framework, a knowledge representation schema to represent design processes (Gero 1990). Designing is defined as the transformation of function (F) into the design description of an artefact capable of producing that function. The artefact's attributes and their relationships are labelled its structure (S). In designing, the behaviour of the structure (Bs) is directly derivable from structure. The expected behaviour (Be) provides the agreed means by which function can be achieved independent from structure. It also represents the knowledge about which behaviours of the structure are of interest.

The FBS framework can be applied into a social system to acknowledge the dual nature of design artefacts. Firstly, artefacts may be physical objects with behaviours (B) that one may call 'objective', i.e., properties derived from a structure's materials, topology and dimensions using a causal theory. An example is the strength behaviour of materials used to manufacture the body of a car. Secondly, artefacts may be social objects with behaviours (B) that one may call 'subjective' as they are derived by the designer(s) and by social consensus or norms (Kroes 2003). An example is the luxury status associated to certain brands of cars. The second type of behaviours (B) are often derived by non-designers, in particular in innovative practices by users (Von Hippel 2005).

The next subsections introduce in general terms the three main system components of our framework shown in Figure 1 including designer agents, fields of adopter groups, and domains or repositories.

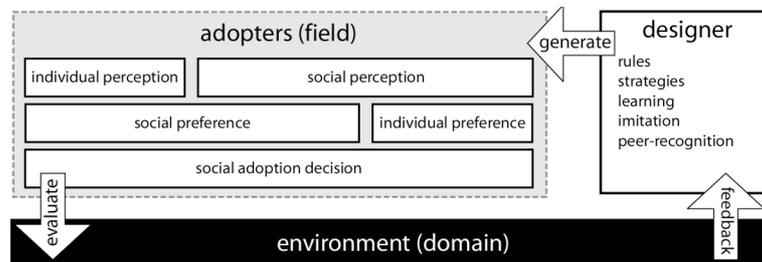


Figure 1. A multi-agent architecture that implements a social view of creativity.

2.2.1 Designers

Individual designers are represented by computational agents whose role is to specify the description (D) of new artefact structures (S). In certain design domains such as virtual design, designers not only provide descriptions but also build artefacts, so at least in that sense one can conflate design with production. Other design domains may require a differentiation between built and non-built artefacts to enable the study of certain phenomena. In our

framework, we adopt the former viewpoint and interpret design output as directly available to and evaluated by societies. In this sense, ‘synthesis’ can be defined as the use of expected behaviour (Be) in the selection and combination of structure based on a knowledge of the behaviours produced by that structure (Bs).

$Be \rightarrow S$

Individual designers can also be said to carry on ‘analysis’ of design artefacts, that is, the determination of behaviours produced by structure (Bs), which draws from existing knowledge of the behaviours produced by different structures and their combination.

$S \rightarrow Bs$

Structure is represented in our framework by simple two-dimensional shapes. This representation is chosen because it supports generation and evaluation mechanisms based on intuitive visual geometric features. It also supports multiple perceptions and shape emergence. As a result, it enables experimentation with some of the key aspects of design problems in multi-objective decision making.

Behaviour is represented by geometric and topological variables whose values are derivable from such two-dimensional shapes and their combinations. Structural behaviour (Bs) is directly obtained from structure (i.e., two shapes with equal left-side coordinates yield a behaviour of alignment). Expected behaviour is represented by geometric preferences, which can be attributed based on different perceptions of design artefacts, and which can be manipulated by groups as the next subsection describes. Behaviour in our framework is a matter of degree and is determined by numerical values assigned to design artefacts based on geometric criteria, i.e., “how well an artefact ‘performs’ rotation or reflection”.

Figure 2 shows a sample artefact based on a two-dimensional representation, and a number of structure features perceived by agents.

Each table is inserted in the text after the first reference to it. Tables are numbered and table captions (in 10 pt Times New Roman are placed above the table, centred, and have the following style:

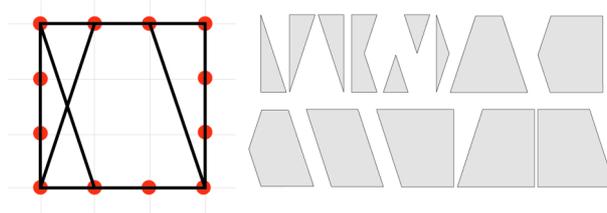


Figure 2. Two-dimensional representation of design artefacts and perceived features

Figure 3 shows a sample set of behaviours represented by geometric relationships between shapes of a set: uniform scale, reflection, and rotation.

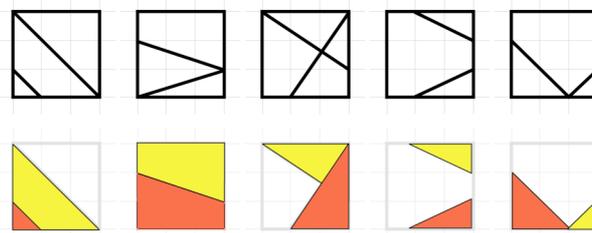


Figure 3. Behaviours represented as geometric relationships in artefact features

A range of relevant issues can be studied in relation to synthesis and analysis processes carried out by designers. For instance, differences in individual abilities, frequencies of behaviour, expertise, relation to competing designers and their knowledge, and strategies are some of the variables that we have started to explore (Sosa 2005). Individual abilities are made operational by parameter ranges that determine how a designer agent generates and applies knowledge to create or modify artefacts. This enables the simulation of scenarios where designer agents competing or collaborating in a system have different abilities and what role these differences play in triggering change cycles. Frequencies of behaviour are determined in relation to other component behaviours such as evaluation. This enables the study of design scenarios where groups take adoption decisions at different frequencies: for instance, packaging and domestic appliances clearly have different generation-evaluation ratios and this may play an important role in determining creative instances and innovation cycles. Expertise can be studied by implementing designer agents with similar abilities but different ‘histories’. This enables the study of possible relation between knowledge and creativity, which have been said to follow an inverted-U shape (Simonton 2003). Individual designers could also be conceived and implemented as teams or firms, delegating different abilities and roles to separate agents.

The particular mechanisms and values considered in our studies have not been used to replicate previous findings; they are mostly hypotheses based in the literature and practice. However, this is often rather ambiguous since observations of social phenomena are usually not specific enough to be directly implemented. In such cases, we set parameters in order to explore a range of possible options and their effects. When these parameter ranges are set to extreme values, we do not assume them to be necessarily realistic; we are more interested in the transition values, which are more likely to capture real situations.

2.2.2 *Field*

Fields in the DIFI framework are social groups that share a domain (Feldman et al. 1994). In our studies, societies are integrated by agents that conduct evaluative behaviour of design artefacts. Namely,

$$\text{Be} \leftrightarrow \text{Bs}$$

The behaviour of the structure (Bs) of an artefact can be compared with the expected behaviour (Be) required to determine if the artefact is capable of producing the functions. This comparison can be seen as a social process of evaluation in design. Field evaluation is an aggregate process in which every adopter agent conducts an evaluation based on a multi-objective function. The product of this evaluation is exchanged in a social group through mechanisms of social influence based on threshold of behaviour (Granovetter 1978). Adopter agents need not have a standard evaluation behaviour, a range can be implemented by distributing different perceptions and different individual preferences randomly at initial time. These evaluative processes produce an emergent pattern of regular group convergence and interval transformations akin the non-ergodic collective coordination behaviour of the n -dimensional social models discussed earlier.

Adopter groups can be regarded as the source of artefact functions. However, in our models transforming function to expected behaviours (Be) remains in control of the experimenter, who formulates the type of geometric and topological properties and the distribution of random preferences and perception. Expected behaviour (Be) provides the syntax by which the semantics represented by function can be achieved. In our studies, the semantics are experimentally controlled whilst the artificial societies self-coordinate to ‘grow’ solutions. Moreover, we have replicated some of our findings changing those semantics in order to confirm the internal validity of our simulations (Sosa and Gero 2005).

Reformulation can be a change in expected behaviour (Be). The design process can be initiated (formulation) or transformed (reformulation) by social demands (social pressure) or by individual initiative (goal-based, opportunistic). In social groups, individual preferences and perceptions are exchanged. Whilst in our framework the experimenter initialises the design system, the dynamics of the system provide the means for reformulation. For each simulation it is impossible to predict what expected behaviours will emerge in a group, i.e. reformulation is self-organised in a society as an aggregate result of agent interaction.

$$\text{F} \leftrightarrow \text{Be}$$

Figure 4 illustrates how a design artefact can be perceived by different agents. Adopter agents can perceive different structure features of the sample artefact shown in Figure 2 as they build perceptions based on a branch limit used to guide a Hamiltonian search through the line set (Rubin

1974). The resulting closed shapes represent alternative structure features of the design artefact on which adopters will base their evaluation.

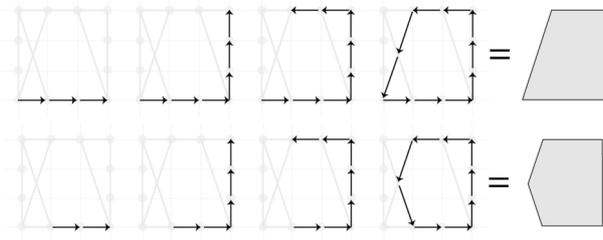


Figure 4. Hamiltonian search conducted by different adopter agents yield different perceptions of a design artefact

As a result of social interaction, adopter populations form aggregate hierarchical social structures. In this framework, these structures are determined by exchanges of preferences, percepts, and adoption decisions. Opinion leaders are defined as adopter agents with high influence over other agents as a result of social interaction. At initial time in a simulation, the set of opinion leaders is empty. The role of opinion leader is given to adopters whose influence is greater than one standard deviation above the mean of group influence. The role of opinion leaders in this framework is to enable interaction between adopters and designers. Firstly, leaders serve as adoption models providing designers with positive feedback for reinforcement learning. Secondly, they become ‘gatekeepers’ of the field by selecting artefacts for entry into the domain or repository, i.e. a collection of artefacts that defines the material culture of a population (Feldman et al. 1994).

Since the number of opinion leaders is, by definition, a small ratio of the adopter population, they are likely to spend more real and computational resources in the analysis of artefacts. This select group of specialised critics also determines behaviours produced by structure (Bs) in order to provide artefact performance feedback to design agents.

$S \rightarrow Bs$

Field variables that we have explored in our studies include the size and the structure of social groups, the types of relationships between members of a group, the formation of hierarchies of influence, and frequencies of evaluation and decision making in relation to design behaviour. Social groups could also be conceived and implemented as teams by combining the roles of evaluation and generation to all the members of a small group. We have applied this view to study the potential effects of social interaction in production blocking in brainstorming groups (Sosa and Gero 2005).

2.2.3 *Domain*

The last model component to study creative design is the ‘cultural’ or epistemological source of a social system (Feldman et al. 1994). One can define domains as repositories of design structure (S) and knowledge (K). In our studies, designers and adopter groups mediate through the domain: some of the design artefacts that are generated by the former and evaluated by the latter may be regarded as high-rated solutions. Likewise, designers may draw from previous examples to guide their design strategies. The contents of a domain illustrate the ‘material culture’ of a society, as they are accumulated collectively by the population over a period of time.

A key threefold aspect of domains is that they are generated by designers, influenced by the adoption patterns of the field, and their content is ultimately determined by experts. Our studies have explored the assumption that certain rules of domains have significant effects in the interaction between individuals and fields. These aspects are set by the experimenter in simulations where all generative and evaluative mechanisms remain constant, and only domain variables are manipulated.

Firstly, the role of knowledge in creative design is addressed by defining two types of access to knowledge generated during the process of designing. These are defined by rules of protection or disclosure of information (i.e. Open-source vs. patenting systems). A series of experiments are conducted to analyse variations in all system levels: how designer agents design and how adopter agents evaluate under these conditions. Secondly, a series of rules and mechanisms of domain entry are explored including the cumulative increase of an ‘entry bar’ by which designers need to produce design artefacts that perform better than previous recent domain entries, and a novelty-seeking rule by which designers need to produce design artefacts that address different evaluation criteria from previous recent domain entries. Thirdly, the representation of design artefacts is modified by varying the size of the design space in order to assess the internal validity of the models.

Domain variables are often dependent variables in our experiments. We are interested in understanding what individual and social factors are likely to have an impact at the domain level including the size of design domains and the distribution of domain entries by designers (if selected artefacts are likely to be generated by all or most designers in the system, or if they may concentrate on one or a few of them).

3. Results

This section presents a summary of the main results obtained in our studies, and their potential relevance to the target phenomena of creativity and innovation in design.

3.1 DESIGNERS

The following subsections illustrate the complementary effects of individual and social aspects in the system.

3.1.1 Change Agents

One of the main aspects under inspection in our studies has been the role of designers as social change agents. Our results demonstrate in simple models of decentralised behaviour that dissenters can trigger change cycles in a bottom-up direction in a social group. The predominance of convergent behaviour in a population can be justified by its role as a key sense-making social element (Boyd and Richerson 1995). According to these results, ratios of up to 10% of dissent in a group are adequate to support group formation and cyclic transformations. When the possible number of individuals engaged in dissenting behaviour in human societies is considered, official census show that the ratio of creative occupations is a marginal proportion of the total population (United States Census Bureau 2000). Less rigorous definitions still yield a similar ratio of creative professions that aim to do things differently compared to “a vast majority engaged in doing the same things better” (Florida 2002).

This view of a minority of practitioners as change agents of their societies is pervasive in the literature. The principle of marginality has been used to imply that asynchrony or dissent is associated with creative behaviour (Gardner 1993). Moreover, creativity has been defined as a ‘dialectical antithesis to intelligence’ (Sternberg 2001), where intelligence is measured by adaptation to the customs of a society and creativity by the transformation of these customs. An implication of such a view is that creative individuals are ‘a threat to the intellectual, social, and economic orders that societies create’ (Sternberg 2001).

When creative designers are regarded as a minority group of dissenters, the effects of manipulating the rate of dissent in multi-agent models support the idea of creativity as a property of systems rather than isolated individuals since increasing the number of dissenters does not increase the rate of collective change linearly (Sosa 2005). Rather, we have shown that there may be a group-level ‘ceiling’ to the frequency of change that a group supports. Rates of dissent over such a threshold impede the basic processes of communication that generate the formation of coherent groups.

3.1.2 Individual Abilities

Although these agent models work with extremely simple generalisations, the results are consistent with the low predictability found in relation to individual differences measured in isolation (Ross and Nisbett 1991). This is typically expressed by low statistical correlations between measured

individual differences on a given trait and observed behaviour in a situation that plausibly tests that dimension. For most novel behaviours, the predictive coefficient of individual differences is not significant (Ross and Nisbett 1991). This is not to imply that individual differences do not matter, but to indicate that their treatment as a sufficient condition of high performance has been probably exaggerated and oversimplified (Ceci and Williams 1999).

The role of individual differences can be considered in an additional way in social simulation. Experimentation with two types of individual abilities of designers has shown their insufficiency as predictors of task performance when individuals are considered as part of a dynamic group. Those experiments illustrate a key characteristic of complex systems: non-linear causality. Whilst initial individual differences stabilise over time due to contingencies modelled as stochastic processes, the potential effects of learning mechanisms further lessen the strength of initial individual differences. Our models demonstrate that learning and development of abilities allow individuals to circumvent their capacity limits, rendering some innate limitations largely irrelevant. This is consistent with the notion that instruction, support and practice often appears to be more important than innate talent in expert performance (Ericsson 1999).

Our studies have also suggested that an increase of individual traits need not be proportional to the effect of individual behaviour (Sosa 2005). For individual abilities of designers to adequately account for effects at the group level, differences between individuals would need to be considerably high. This would be inconsistent with what is known about distributions of intelligence and skills (Sternberg 1985). More importantly, even when certain abilities may account for some aspects of behaviour and possible effects, these need not be related to creativity. An example is provided in our modelling of knowledge formulation in design, where individuals with larger knowledge bases (more expertise) need not be more successful in measures potentially relevant to creativity and innovation than those with less knowledge available. Other researchers report similar types of interaction between expertise and creativity (Ericsson 1999). Furthermore, increases of individual abilities can also be associated to the improvement of competitors. Our models suggest that the degree of differences between competing designers need not have a direct effect in the triggering of social change. This observation can be related to the notion of 'spillovers' in innovation research. When individual agents in our experiments are assigned extremely high abilities, competing individuals with otherwise unchanged abilities also increase their performance as a side-effect of sharing information with more able competitors. Relevant empirical studies also conclude that competitors benefit from innovation within their industries regardless of its source (McGahan 1999).

3.1.3 Opportunities

Individual behaviour may combine with favourable circumstances to trigger social change. In CA models, such conditions are a product of the random location of cells on the environment. In contrast, MABS experiments capture the idea that the appropriateness of design behaviour in a system of generation and evaluation of design is collectively defined by the social group within which designers operate. A prime example of favourable conditions is the aphorism of the innovator standing ‘on the shoulders of giants’ attributed to Isaac Newton.

A key assumption in our studies has been the combination of habituation and novelty-seeking behaviour of adopters. Habituation refers to the tendency of adopters to increase their preferences for features with high scores, whereas novelty seeking is the process that allows adopters to update their preferences as a result of social convergence. If a design solution is considered as a compromise between conflicting objectives, it is generally assumed that a new artefact will displace an existing one when adopters perceive an advantage that the new holds over the existing artefacts (Rogers 1995). However, it has been shown that people tend to adapt to inconveniences or problems associated with long-existing artefacts (Petroski 1992). In our framework, causality of group change is attributed in two complementary directions. Firstly, the novelty-seeking behaviour of adopters demands the generation of new solutions by designers. Secondly, designer agents proactively seek new solutions that may reshape demand. This twofold mechanism in our model accounts for a type of non-ergodic ‘cultural drift’ (Axelrod 1997).

3.1.4 Peer Influence

An important component of creativity has been identified in the process of peer judgement (Amabile and Hennessey 1999). This is addressed in our studies mainly through the concept of influence between designer agents. During a system run, the cumulative number of instances where a designer receives recognition from imitative peers is recorded. The strongest effects in peer influence in our studies are registered from variations of design rate, where the frequency of design activity produces a linear correlation to peer recognition when plotted in a log-log scale. Namely, when design activity takes place frequently in comparison to gatekeeping and adoption processes, mean peer recognition increases nearly six times higher than on average. In contrast, as design activity gradually slows down, recognition between peers rapidly approaches the standard value recorded under all other independent variables considered. The effects of design rate in peer recognition are paralleled in our studies by its effects in the formulation of knowledge. Namely, frequent design cycles yield large knowledge bases and a high level of recognition between designers.

One way in which this insight could be verified empirically is to compare recognition between competitors in design domains with different mean lengths of product development cycles. Imitation of artefact features or payment of copyrighted material can be used as indicators of peer recognition in design. According to our studies, these indicators would be higher in domains where redesign occurs frequently as in car design than in domains where redesign is more sporadic as in truck design. In addition, innovation could be expected to be higher in design domains where larger knowledge bases are likely to exist.

3.1.5 Summary

An interdependent relationship between individual behaviour and the conditions and effects at the social level is observed in a number of findings from our research. To trigger a global change based on local behaviour, the actions of a change agent are importantly determined by necessary conditions that lie outside its control (i.e., previous knowledge). Once these adequate conditions exist, they ought to be perceived by the individual who has to be sufficiently able to execute the corresponding action. The frequency, independently of the actual content, of the action can determine influence between peers and the decisions and strategies in the design process.

Our studies demonstrate that at least some of the effects of design behaviour in society are determined by a range of situational conditions. The entire process can be seen as a match or adaptation between the individual and the social levels. This underlines the cautionary note that giving emphasis to either part of this chain of causation is misleading; an example being the recurring controversy whether causality of creativity originates at the individual or at the social level (Lloyd and Snelders 2003).

Other models of creativity from an evolutionary perspective have interpreted differences in creative activity among individuals as arising from a combination of innate and experiential factors (Findlay and Lumsden 1988). This view is consistent with the emphasis on the role of development. Our work in this regard demonstrates that the exceptionality of individuals that trigger group changes can be explained by a combination of individual and situational conditions. In relation to the individual processes of synthesis and analysis, the following can be summarised:

- Synthesis occurs less frequently than analysis and evaluation in creative design.
- Different synthesis processes can lead to creativity. No single process or set of processes can guarantee the generation of a creative solution, as the determination of creativity is product of two-level interaction in the system. There are a number of potential creative synthesis

processes, those which are relevant in place and time within a social environment are the ones that trigger cycles of change.

- The relationship between a synthesis process and its effects in evaluation is likely to be non-linear.
- A synthesis process that is not creative within a given situation, can be considered as creative and trigger a cycle of innovation in the same society if a situational factor or a set of situational factors change.

3.2 FIELD

The field has been defined in our studies as the collection of individuals that participate in the definition of a standard of what constitutes novelty and quality or utility, the two canonical elements in the definition of creativity (Feldman et al. 1994; Runco 2004). In this subsection some of the key aspects addressed in our work are analysed.

3.2.1 Group Size and Group Structure

Our studies have shown that the size of a social group may have key effects on the interaction between generators and evaluators of solutions. In CA models, very small populations do not support interaction between different individuals limiting the diffusion process. The apparent reason is that in smaller groups insufficient diversity yields incompatibility between evaluators that influence each other's decisions. In contrast, large populations where only local interaction takes place do support the exchange of opinions but take exponentially long periods to form consensus (Axelrod 1997). A clear implication from this result could be that large populations are likely to develop means of mass communication as a way to promote group coherence, an aspect that is outside the scope of CA modelling.

Whilst group size yields no further qualitative differences in our models, a constant population size is found to cause substantial differences when the arrangement of its members varies. One aspect is that with a constant type of local conditions, different common neighbours or 'friends-of-friends' network configurations have different effects. Experimentation with different grid structures has shown that besides local configuration, the degree of contact between individuals has an important effect on how new ideas are disseminated. When the neighbours of individuals are unlikely to be in contact with each other, diffusion can be expected to require substantially longer times and have qualitatively different outcomes than when the 'degree of separation' is lower. The degree of separation can be measured by the ratio of common neighbours between individuals in a social network.

Studies of field structure have served as a basis for the type of agent relations implemented in our studies. These assumptions are based on the

widely accepted notion of the strength of social ties (Granovetter 1973). Ties represent contact between social actors represented by nodes in social networks (Wasserman and Faust 1994). One way to define the strength of social ties is by their duration over time, i.e., the probability that two nodes in a social graph remain connected over a period of time (Marsden and Campbell 1984). These assumptions account for the observation that for any given design field, potential adopters interact in a number of different social networks with different tie strengths such as kinship networks (strong ties) and acquaintance networks (weak ties). We have shown a number of insights in relation to tie strength and innovation including patterns in the design and adoption of artefacts, and the distribution of prominence for designers. In sum, our results reinforce the idea that populations where members are part of various contact networks are more likely to support the emergence and diffusion of new values. Recent studies of entrepreneurs consistently report that the most creative individuals spend more time than average networking with a diverse group that includes acquaintances and strangers (Ruef 2002). A combination of strong and weak ties is thus proposed as conducive to creativity.

A similar interpretation suggests that weak social ties facilitate the introduction of novel ideas (Florida 2002). In our studies, behavioural variety is supported by weak social ties where diversity of adoption opinions is higher than in equivalent social groups with strong ties. Others have suggested that societies that support more behavioural variety tend to go through rapid adoption cycles of new artefacts (Reinstaller and Sanditov 2004). Our studies further confirm that both the speed and scope of diffusion highly depend on the structure of a society.

3.2.2 Opinion Leaders

The behaviour and effects of opinion leadership in our studies contribute to the discussion of the link between individual designers and their societies. Biographic studies suggest that in more hierarchical fields (i.e., “where a few powerful critics render influential judgments about the quality of work”) it is easier for a small number of creators to emerge and gain recognition and influence (Feldman et al. 1994). In agent societies with strong social ties, uneven hierarchies generate powerful opinion leaders that exert the role of gatekeepers to the domain. In contrast, in social networks with weak ties, influence is distributed among adopters and the expert judgements tend to vary over time. Consistent with Gardner’s (1994) observation, the former social arrangement generates higher variance in the distribution of prominence whilst the latter yields more egalitarian distributions in our systems.

3.2.3 Evaluation Distribution

In our studies aggregate adoption decisions of a population are used to determine the distribution of adopters by designer. If the variance of adoption is high, then the artefacts generated by a few designers concentrate a high proportion of the adoption choices during a simulation run. If the variance of adoption is low, then adopters are said to distribute their choices across all available artefacts. In the former case prominence and differentiation are expected to be high whilst in the latter competition indices are likely to be high.

Our studies show that the distribution of adoption decisions is importantly determined by social factors such as the frequency of contact between adopters. In our studies when social connections between members of an evaluation group are replaced, social mobility is determined by the rate of link replacement. When no social mobility is possible, our studies show that variance of adoption rapidly increases to a mean level of 100%. However, even small amounts of social mobility proved sufficient to normalise this distribution. These differences in adoption variance are consistent with parallel effects of social ties in opinion leadership and domain characteristics.

3.2.4 Summary

Design behaviour has been addressed in the literature mainly as a cognitive phenomenon. This has advanced our understanding of creative design at the individual level but has shed little understanding on this activity as part of a social system. The general conclusion from our exploration of design as a social activity is summarised by the proposition that the 'creative act' does not end with the specification of a design solution. The synthesis of an artefact is only the starting point of a poorly understood process where creativity turns into innovation in the link between individual and social action, i.e., 'design is a cognitive and a social process'.

The social forces acting on the creative individual can be classified in two periods, i.e., the earlier period in the production of ideas and the later period in their dissemination and evaluation. The relationship between collective factors and individual expression is extremely complex (Rudowicz 2003). Arguably, the main insight of situated behaviour is the principle that the same individual design behaviour can generate solutions that are regarded as creative within one social setting but not within a different one. In other words, macro conditions may provide the bases for particular generative processes, or they may facilitate particular effects on evaluative processes. The strongest evidence for this principle is the extemporaneous recognition of creativity. Whilst design artefacts remain unchanged, the social and cultural conditions may evolve to the point where evaluators are ready for such solutions.

One of the aims in this type of studies is to show that equivalent individuals and solutions could be considered creative or not by equivalent social groups depending on situational factors. This is an important challenge that would demonstrate that the creativeness of a solution is not an inherent property but one ascribed over time by others in a process which is subject to a range of circumstances.

In relation to the individual processes of synthesis and analysis, the following can be summarised:

- Who, how, and how many agents assess a design artefact will affect the outcome of such evaluation. If evaluators deliberate in large groups, solutions considered creative are likely to be more in number and more different from each other (a more diverse set). If evaluation is done without deliberation or in small groups, the result is likely to be a smaller set of creative solutions and more similar to each other. Namely, the set of expected behaviours (Be) and structure behaviours (Bs) are larger and of higher complexity in the former situations.
- Reformulation is likely to depend largely on social interaction. Expected behaviour (Be) can be shaped by social factors such as the types of social ties in a group, the structure of the group, and the mechanisms in place to define and operate opinion leadership. A Be-Bs mismatch can lead to new design processes (namely synthesis), or to new problems (formulation).
- Lastly, experts or critics in a social group (designers or not) can generate new knowledge via analysis by deriving new structure behaviour from design artefacts. Technological advances in materials and production are sample sources of new knowledge.

3.3 DOMAIN

Domains represent the epistemological level in a systems model of creativity (Csikszentmihalyi 1988). Whilst no formal criteria have been proposed for identifying a domain, in our studies design domains are defined as repositories or collections of artefacts and knowledge accumulated by a population over a period of time.

3.3.1 Knowledge

The learning mechanisms of design agents enable them to formulate knowledge in relation to the transformation of artefacts. Our studies have addressed two types of access to this knowledge or information generated during the process of designing. These are defined by rules of protection or disclosure of information.

When design activity is very frequent the generation of new knowledge increases. With small decreases in frequency of design activity, the size of knowledge bases reaches a stable level. The mechanism at work seems to be the collective production of knowledge. A parallel pattern is observed when

designers have access to the knowledge generated by others. Disclosure of information causes an increase in generation of knowledge. Moreover, in both experiments other associated effects are observed: frequent rates of design activity and public disclosure of information yield lower variance of domain entries as well as higher domain scores and complexity. Seemingly, higher quality may be associated to the contributions of various sources supported by the disclosure of knowledge.

3.3.2 *Gatekeeping*

In practice, gatekeepers are individuals authorised to qualify the merits of creative solutions including their novelty and feasibility. Apart from patent examiners, other types of gatekeepers in design include venture capital firms, exhibition curators, journal editorial committees, and competition juries. Approval or endorsement of gatekeepers may be necessary to turn a new idea into an available product. Nonetheless, little is known about the role of gatekeeping in a) promoting or deterring the generation of creative solutions and b) initiating or promoting their diffusion and the social ascription of the 'creative' label to their creators. Gatekeepers such as patent examiners base their decisions *prima facie*, on references to other patents and ordinary skills, and on declarations from experts in the field. However, articulating these evaluations is often problematic and in many cases criteria are updated or made explicit based on litigations.

Gatekeeping in our studies is considered an emergent role that adopter populations assign to some of their members as an aggregate result of social interaction. In particular, influence of adoption opinions is taken as the condition to allocate the gatekeeping role, i.e., influential adopters become gatekeepers of the domain (Sosa and Gero 2004a). Our models show that the role of influential adopters as gatekeepers can be important in the rate and quality of design behaviour and the relation between designers and adopters. In particular, disclosure of information was shown to render larger domains with higher mean scores. This type of access also discourages the concentration of experts' selections on few designers. Therefore, under systems of high protection of information experts can be expected to concentrate their choices. Scores assigned by gatekeepers to domain entries are also higher when adopters' choices are more individualised.

A number of insights are motivated from our exploration of gatekeeping. Firstly, higher rates of gatekeeping generate a higher number of domain contributions and a decrease in the variance of contributors. This lower concentration of prominence is interpreted as more designers being responsible for contributing to the domain. This is in contradiction to the Price Law which states that the square root of N , where N is the number of contributors in the field, is the number of individuals who will account for 50 percent of creative contributions (Simonton 2003). Further research is

necessary to understand the conditions under which these apparently contradictory patterns may occur.

3.3.3 Domain Size and Distribution

The selection of entries by gatekeepers in our studies is assumed to be based on an incremental scale where once a solution is presented and chosen for inclusion in the domain, other solutions even with identical features are not considered of merit. In fields of creative practice these are in fact labelled as forgeries. The score assigned to an entry becomes the new entry threshold for future candidates. For new artefacts to gain access, two conditions are considered in our studies: entries must receive a higher score in the same features than existing entries or they must present advantages in features other than those by which previous artefacts were chosen. An additional mechanism implemented in our framework addresses the decay of the entry threshold. The assumption is that as simulated time lapses, with no new entries being selected the entry bar gradually decays.

The main consideration on domain characteristics in our studies centred on their role as dependent variables. Various aspects in our models are found to determine the quantity and quality of domain entries including individual differences and situational factors such as rates of behaviour and type of access to knowledge. Our findings suggest that quantity (number of domain entries) and quality (score and complexity of domain entries) need not be correlated. For instance, the mean scores assigned by gatekeepers to domain entries are higher when adopters' choices are more individualised but no significant changes in domain size are observed. However, frequent adoption cycles generate both larger domains and higher scores.

In sum, situational aspects that may facilitate domain entry include frequent adoption decisions, frequent expert selection, disclosure of information between designers, number of adopters, and the strength of their ties (Sosa and Gero 2004b).

3.3.4 Artefact Structure

The effects of manipulating the composition of solutions or artefacts have been assessed in our framework. The main conclusion is that under equivalent processes of diffusion, values that consist of a few variables a) tend to spread rapidly through a population, but b) reach only a segment of the population. In contrast, artefacts that are formed by a large range of variables require longer periods to be spread but provide a large number of options of which gradual acceptance is supported. Number of variables of an artefact refers to the range of possible features that can be assigned a number of values. Examples of this distinction in design artefacts are first-generation of consumer products such as bicycles, cars, digital cameras, telephones and

personal computers which have tended to have a minimum of options whereas in subsequent versions more product features and optional accessories become available. This principle suggests that artefacts such as early consumer products would tend to be adopted relatively fast but only by small segments of the market whereas second and third-generation products would take longer but would reach a wide spectrum of consumers.

Increasing the number of variables or features of an artefact and not the range of values or traits for each variable is likely to affect the diffusion process (Sosa and Gero 2003c). Artefacts with a combination of more features and less traits present a balance between diffusion time and scope. As more features are added, diffusion times increase without changes in scope. Likewise, increasing the number of traits causes minor changes in diffusion times whilst significantly affecting the scope of diffusion. A balance between number of variables and value range is expected to provide optimal conditions for diffusion. One way to explain this assumed optimal balance is through the study of compatibility and complexity in innovation studies. Compatibility has been defined as the perceived degree of consistency between existing and new solutions, whilst complexity of an innovation generally refers to the degree to which it is perceived as difficult to understand and use by potential adopters (Rogers 1995).

The general assumption in the literature is that high compatibility and low complexity facilitate innovation (Rogers 1995). These two requirements support our findings since design artefacts with more potentially common features can be expected to be more compatible with existing solutions. On the other hand, artefacts with a smaller range of values per variable can be expected to be perceived as less complex. Table 1 summarises the notion that artefacts that spread relatively fast and have a larger scope of diffusion would consist of more features and less traits per feature. Such artefacts would be potentially highly compatible with existing solutions, yet have low complexity.

TABLE 1 Characteristics of artefacts with rapid diffusion speed and large scope

ARTEFACT TYPE	DIFFUSION SPEED	DIFFUSION SCOPE
High compatibility + low complexity	Intermediate	Medium

Our findings suggest that design artefacts with a large number of variables require longer initial stages of adoption, or a larger critical mass of early adopters to reach the ‘tipping point’, i.e. the stage in the diffusion process where a majority of individuals rapidly adopt a solution. In contrast, the diffusion of artefacts with a small number of variables would reach this point with a smaller group of early adopters.

The ‘tipping point’ in the case of artefacts with a small range of variables in our studies reaches only a small portion of the universe of potential adopters. For artefact structures with more features, diffusion only takes off later but it reaches larger adopter groups. The importance of this distinction is that it only takes into account the type and number of characteristics of the artefacts being adopted preceding any consideration of their actual values, their designers, or the adoption population.

3.3.5 Summary

Our studies reveal a comprehensive role of domains in the link between individual behaviour and social change. These collections from which individuals retrieve existing information and fields incorporate changes may have significant qualitative and quantitative differences depending on a number of factors, most of which have been only marginally addressed in the literature.

A prevalent assumption is that creativity can be estimated from the creator’s total output or from the number of works commended by experts (Simonton 2003). However, individual differences are only one of the factors that determine the quantity and quality of a domain. The 1,093 patents granted to Thomas A. Edison (Israel 1998) need not indicate much about his individual characteristics. Some of the factors addressed in our studies that may be responsible for such exceptional contribution include a) spillovers from other inventors, b) social characteristics that value and promote production, c) frequent rates and diverse sources of gatekeeping including investors, d) rapid increase of target population size, and e) disclosure of new knowledge. The combination of these factors is likely to determine the output and distribution of prominence across competitors.

Extensions to these models include more than one society having contact through their domains, which could enable the modelling of distant analogies in creativity (Qian and Gero 1995). Other extensions could include further domain mechanisms such as when a new solution renders some or all past entries obsolete.

3.4 DISCUSSION

These computational studies point towards a promising line of inquiry focused on the complex interaction between individuals, fields and domains. The most important theoretical construct that frames this interaction is the notion of ‘design situations’. As a result of the dominant individualistic focus in the literature, important questions have been under-emphasised, specifically the study of ‘creative situations’ which Amabile (1983) defines as ‘circumstances conducive to creativity’.

A design situation represents the combination of individual and external factors as construed in a context. A situation in design can be defined as the confluence of individual and external conditions within which generative and evaluative behaviour is determined. Situations can be characterised as conducive to a number of effects including prominence, influence upon peers, increased rates of creation, rapid diffusion curves, etc.

An important implication of the notion of design situations is the degree to which individuals are able to choose and manipulate aspects of the situations within which they operate. An important role of individual differences may be in the disposition to choose or transform certain situations (Ross and Nisbett 1991). Different scenarios can be described based on our studies such as:

- Situations where one designer is likely to concentrate adoption
- The distribution of adoption choices by designers does not seem to be significantly affected by individual differences in our framework.
- Situations where designers are likely to receive high peer influence
- Recognition from peer designers emerges when features of an exemplary artefact are copied by other designers.
- Situations where one designer is likely to concentrate contributions
- In fields of frequent design rate, contributions selected by gatekeepers to enter the domain originate from a small number of designers.
- Situations where adopters are likely to be more satisfied
- When the individual bias of adopters is a strong factor of the adoption decision, their satisfaction (as a post-adoption measure) is likely to increase, but it is also very unpredictable.
- Situations where more contributions of high quality are likely
- Where quality is defined by the scores assigned by gatekeepers to domain contributions. .

3.4.1 The Power of Situations

Situational factors need not be externally imposed but could be chosen and modified by designers as a result of their experience. Namely, a designer could choose to target smaller/larger populations, to target groups with stronger/weaker social ties, to exercise design updates more/less frequently, to encourage opinion leaders to manifest their opinions more/less frequently, etc. Obviously these are factors only partially accessible to the designer, some require external change or negotiation with other stakeholders. This research aims to draw attention into these types of factors and to demonstrate an experimental system of analysis. Future research will be extended to include other situational factors that can determine creativity and innovation in important ways. Whilst the likely effects of situational factors can be

identified, the power of a situation has been regarded as variable (Bem and Allen 1974).

4. Discussion

This paper has presented a framework that enables experimentation with the dual nature of creativity in design: the derivable attributes of objects and the social ascription by subjects. This framework applies two influential models in the fields of creativity and design. Experimentation with this framework demonstrates how computational social simulation can be applied to model design beyond purely cognitive processes. It provides alternative computational means to explore a complex subject, and results should be taken carefully as hypotheses rather than theoretical principles. Further work is necessary where experimenters need to try different assumptions, views, applications, domains, and system components.

An 'in-silico' approach of this type can complement in-vitro (laboratory) and in-vivo (biographical) studies; they can inform each other to test results, to build alternative hypotheses, to design new experiments, to consider other variables; and to conceive the relation of different processes particularly at different levels of analysis.

References

- Amabile, T: 1983, *The Social Psychology of Creativity*, Springer-Verlag, New York.
- Amabile, T and Hennessey, BA: 1999, Consensual assessment, in MA Runco and SR Pritzer (eds), *Encyclopedia of Creativity*, Academic Press, San Diego, pp. 347-360.
- Axelrod, R: 1997, The dissemination of culture: A model with local convergence and global polarization, *The Journal of Conflict Resolution* **41**(2): 203-226.
- Bem, DJ and Allen, A: 1974, On predicting some of the people some of the time: The search for cross-situational consistencies in behavior, *Psychological Review* **81**: 506-520.
- Boden, M (ed.): 1994, *Dimensions of Creativity*, MIT Press, Cambridge.
- Boyd, R and Richerson, PJ: 1995, Why does culture increase human adaptability? *Ethology and Sociobiology* **16**(2): 125-143.
- Ceci, SJ and Williams, WM: 1999, *The Nature-Nurture Debate: The Essential Readings*, Blackwell, Malden.
- Conte, R, Edmonds, B, Moss, S and Sawyer, RK: 2001, Sociology and social theory in agent based social simulation: A symposium, *Computational and Mathematical Organization Theory* **7**(3): 183-205.
- Csikszentmihalyi, M: 1988: Society, culture, and person: a systems view of creativity, in RJ Sternberg (ed.), *The Nature of Creativity, Contemporary Psychological Perspectives*, Cambridge University Press, pp. 325-339.
- Ericsson, KA: 1999, Creative expertise as superior reproducible performance: Innovative and flexible aspects of expert performance, *Psychological Inquiry* **10**(4): 329-333.
- Feldman, DH, Csikszentmihalyi, M and Gardner, H: 1994, *Changing the World: A Framework for the Study of Creativity*, Praeger, Westport.
- Findlay, CS and Lumsden, CJ: 1988, *The Creative Mind*, Academic Press, Orlando.

- Florida, RL: 2002, *The Rise of the Creative Class: And How It's Transforming Work, Leisure, Community and Everyday Life*, Basic Books, New York.
- Gardner, H: 1993, *Creating Minds: An Anatomy of Creativity Seen Through the Lives of Freud, Einstein, Picasso, Stravinsky, Eliot, Graham, and Gandhi*, BasicBooks, New York.
- Gero, JS: 1990, Design prototypes. A knowledge representation schema for design, *AI Magazine* **11**(4): 26-36.
- Gero, JS: 2000, Computational models of innovative and creative design processes, *Technological Forecasting and Social Change* **64**(2-3): 183-196.
- Granovetter, M: 1973, The strength of weak ties, *American Journal of Sociology* **78**(6): 1360-1380.
- Granovetter, M: 1978, Threshold models of collective behavior, *American Journal of Sociology* **83**(6): 1420-1443.
- Israel, P: 1998, *Edison: A Life of Invention*, John Wiley, New York.
- Kroes, P: 2003, Screwdriver philosophy: Searle's analysis of technical functions, *Techné* **6**(3): 22-35.
- Kuhn, TS: 1974, Second thoughts on paradigms, in F Suppe (ed.) *The Structure of Scientific Theories*, University of Chicago Press, Chicago, pp. 459-482.
- Liggett, TM: 1985, *Interacting Particle Systems*, Springer-Verlag, New York.
- Lloyd, P and Snelders, D: 2003, What was Philippe Starck thinking of? *Design Studies* **24**(3): 237-253.
- Marsden, PV and Campbell, K: 1984, Measuring tie strength, *Social Forces* **63**(2): 482-501.
- McGahan, AM: 1999, Competition, strategy, and business performance, *California Management Review* **41**(3): 74-101.
- Petroski, H: 1992, *The Evolution of Useful Things*, Knopf, New York.
- Qian, L and Gero, JS: 1995, An approach to design exploration using analogy, in JS Gero and ML Maher (eds) *Computational Models of Creative Design*, University of Sydney, Key Centre of Design Computing, pp. 3-36.
- Reinstaller, A and Sanditov, B: 2004, Social structure and consumption: on the diffusion of consumer good innovation, in J Archer (ed.) *DRUID Summer Conference 2004 on Industrial Dynamics, Innovation and Development*, Elsinore, Denmark.
- Rogers, EM: 1995, *Diffusion of Innovations*, Free Press, New York.
- Ross, L and Nisbett, RE: 1991, *The Person and the Situation: Perspectives of Social Psychology*, Temple University Press, Philadelphia.
- Rubin, F: 1974, A search procedure for Hamilton paths and circuits, *Journal of the ACM* **21**(4): 576-580.
- Rudowicz, E: 2003, Creativity and culture: a two way interaction, *Scandinavian Journal of Educational Research* **47**(3): 273-290
- Ruef, M: 2002, Strong ties, weak ties and islands: structural and cultural predictors of organizational innovation, *Industrial and Corporate Change* **11**(3): 427-449.
- Runco, MA: 2004, Creativity, *Annual Review of Psychology* **55**(1): 657-687.
- Schumpeter, JA and Clemence, RV: 1989, *Essays: On Entrepreneurs, Innovations, Business Cycles, and the Evolution of Capitalism*, Transaction Publishers, New Brunswick.
- Simonton, DK: 2000, Creativity, *American Psychologist* **55**(1): 151-172.
- Simonton, DK: 2003, Scientific creativity as constrained stochastic behavior: the integration of product, person, and process perspectives, *Psychological Bulletin* **129**(4): 475-494.
- Sosa, R: 2005, *Computational Explorations of Creativity and Innovation in Design*, PhD Thesis, Key Centre of Design Computing and Cognition, University of Sydney.

- Sosa, R and Gero, JS: 2002, Cellular automata models of creative design situations, in JS Gero and F Brazier (eds) *Agents in Design 2002*, Key Centre of Design Computing and Cognition, University of Sydney, Australia, pp. 165-180.
- Sosa, R and Gero, JS: 2003a, Design and change: A model of situated creativity, in C Bento, A Cardoso and JS Gero (eds) *Approaches to Creativity in Artificial Intelligence and Cognitive Science*, Acapulco, pp. 25-34.
- Sosa, R and Gero, JS: 2003b, Social change: Exploring design influence, in D Hales, B Edmonds, E Norling and J Rouchier (eds), *Multi-Agent-Based Simulation III*, Springer, pp. 106-119.
- Sosa, R and Gero, JS: 2003c, Social change: Exploring design influence, in D Hales, E Norling and J Rouchier (eds) *Multi-Agent Based Simulation Workshop*, Melbourne, pp. 106-119.
- Sosa, R and Gero, JS: 2004a, A computational framework for the study of creativity and innovation in design: Effects of social ties, in JS Gero (ed.) *Design Computing and Cognition '04*, Kluwer Academic Publishers, Dordrecht, pp. 499-517.
- Sosa, R and Gero, JS: 2004b, Diffusion of creative design: Gatekeeping effects, *International Journal of Architectural Computing* 4(4): 518-531.
- Sosa, R and Gero, JS: 2004c, The role of gatekeepers in creativity, in P Gervas and K Moy Gupta (eds.) *Computational Creativity Workshop*, Universidad Complutense de Madrid, pp. 257-268.
- Sosa, R and Gero, JS: 2005, Group brainstorming: Insights from computational social simulation, *in preparation*.
- Sternberg, RJ: 1985, *Beyond IQ: A Triarchic Theory of Human Intelligence*, Cambridge University Press, Cambridge.
- Sternberg, RJ: 1999, *Handbook of Creativity*, Cambridge University Press, Cambridge.
- Sternberg, RJ: 2001, What is the common thread of creativity? Its dialectical relation to intelligence and wisdom, *American Psychologist* 56(4): 360-362.
- United States Census Bureau: 2000, *Indexes of Industry and Occupations*, Washington, D.C.
- Von Hippel, E: 2005, *Democratizing Innovation*, MIT Press, Cambridge.
- Wasserman, S and Faust, K: 1994, *Social Network Analysis: Methods and Applications*, Cambridge University Press, New York.
- Wolfram, S: 1986, *Theory and Applications of Cellular Automata: Including Selected Papers, 1983-1986*, World Scientific, Singapore.
- Wolfram, S: 2002, *A New Kind of Science*, Wolfram Media, Champaign.
- Wooldridge, MJ: 2002, *An Introduction to Multiagent Systems*, John Wiley, Chichester.