Towards a Computational Analysis of Style in Architectural Design

Content Areas: Qualitative encoding, information theory, agents, social networks.

Julie R. Jupp and John S. Gero
Key Centre of Design Computing and Cognition
University of Sydney NSW 2006 Australia
{john, jupp_j}@arch.usyd.edu.au

Abstract

This paper proposes a computational model of design that attempts to capture within a social context two important aspects of style: 'content' and 'manner'. We present a characterisation of style for the artefact based on a framework that consists of information theoretic measures. We discuss the benefits the study of social networks offers a computational analysis of both aspects of style. It is our aim to bring style as 'content' and style as 'manner' together using this approach.

1. Introduction

Research in various domains share problems of formalizing style. In this paper we describe a schema for the computational analysis of *design* style. We utilize both form and social determinants as two fundamental dimensions in design. An appropriate conception of design has been presented as a purposeful, constrained, decision-making, exploration and learning activity [Gero, 1996]. The designer operates within a context, which changes as they explore emerging relationships between designs, their style and the context itself. Style is influential in changing the design context as it enables the designer to extend design knowledge by grouping or classifying existing design artefacts according to some distinguishable properties. The context or the situation is influential in transformation processes that may occur incrementally through acts of imitation or radically through acts of innovation. In this way style acts as an ordering principle in design that allows individual artefacts and processes to be structured, providing order within an otherwise apparently chaotic domain.

Generally, style considers both the 'manner' in which something is done and the 'content' of what is being accomplished [Simon, 1975]. Our analysis of style does not isolate 'manner' from 'content'. Instead we approach style primarily from the viewpoint of design 'content' in order to explore possible processes of action of the individual and interaction with the situation, which may be inferred from the artefact. Since style is a concept based on general agreements of the commonalities, in a design society, it is necessary to consider social relations, that is, the agreements of the individual, school, society or culture. Such an approach to style may in turn reflect potential relations within the design process that transform design requirements into design properties. A computational analysis of style should therefore bring both representation of artefacts and the processes of interaction together.

The problem we are considering in this paper concerns the social dimension of design artefacts and processes construed in terms their stylistic transformations. The domain of this study is the two-dimensional drawing and related activity. The subject of this study is the social aspect of design style and the effects of style knowledge on its transformation. In unifying style as artefact and as process we consider the social context that extends from the agent into the situation. This approach considers the interactions between the agent, the product, and the socio-cultural context. However, a definition of design style emerging as a social construct negotiated among a number of social agents is a nascent approach. Such a method seeks to understand the influences of social phenomenon in terms of the individual actions and interactions.

1.1 Style and the Social Context

Style operates socially in a number of ways. First, the style of an artefact embodies notions of identity that are socially recognized and thus become instances in the symbolic exchange of meaning [Goodman, 1976]. Second, style becomes an influence for individual and collective action [Shapiro, 1961]. Third, styles influence their own transmission and transformation [Knight, 1994]. Style is inclusive of such social relations relative to the individual artefact that address the situation in which designers and design communities function.

One difference between the design artefact and the design process is the level of subjectivity in their social construction. The artefact undergoes an evaluation at many levels, including the individual, the design field and the socio-cultural domain. This makes visible the interaction between the artefact, its environment and the unintended or emergent social reactions. The artefact's style after the design is realised, takes its own course of existence. This feedback makes the design product a valuable analytical vehicle in terms of representing its style. Further, the design artefact as a materialization of the activity is an important factor that influences design knowledge. The style of the design artefact influences the processes of the design agents and their resulting strategies.

This paper explores a computational framework for modelling style that considers both subjective representational constructions as well as objective situational factors. We explore some of what this combined perspective could contribute to a digital characterization of style. This paper is organised in three main parts. The first of these develops the basis for design categorisation and style recognition. We begin by defining a simple model of style applied to architectural design and review current approaches to categorizing design artefacts. In the next part we present the representational framework for style recognition based on information theoretic measures of qualitative features. The final part discusses the structure for the design process in terms of informed decision making in a social context. We explore the processes of interaction in social networks as well as the transformations of style in a design society. The paper closes with a discussion of some insights social networks might have to offer a model of style.

2. A Model of Style

Historical and critical descriptions of architectural design often seek to identify the design style and are concerned with two principal aspects. Firstly, a building may be represented visually from either a two or three dimensional perspective. Secondly, the artefact can be construed in terms of its materiality. Materiality encompasses two systems, the morphology and the situation. In the first part of this model we address aspects of design morphology and in the second part the design situation. The term morphology refers to the materials as well as to the pattern (or structure) in which the material is "modelled". Whilst recognizing alternative approaches to describing architectural artefacts in relation to style, for the purposes of this paper we limit our scope to geometrical and topological patterns and structures. Our approach can be represented by building structure and skin, including walls, partitions and screens. From this point of view morphology can be described in terms such as shape, form, solids, voids, mass and space, or more specifically as the spatial layout. In this study we only deal with two-dimensional representations and more specifically only the walls, partitions or screens and their intersections. However this does not suggest that our methodology is restricted from considering three-dimensional objects such as a complete 3D spatial model. Our approach assumes the representation of the physical artefact. For example a residential building may be represented as a two-dimensional building plan.

The method of formal recognition of style developed here is analogous to a kind of natural language in which conventions are organized into coherent constructs. This idea comes from Arnheim's notion of the drawing as a kind of dialectic [Arnheim, 1993]. Arnheim considers the ability to conceive, plan and present ideas about artefacts to be at the core of design. Thus design knowledge must be transformed from the designer's imagination into some kind of image. A two-dimensional (2D) representation of an architectural plan is an informational artefact. By recognizing an informational artefact's style we aim to clarify the underlying commonalities of structure and conventions manifest within the 2D plan drawing and supply the criteria necessary to determine whether a drawing is an instance of a particular style.

2.1 Key Issues

In order to address how a digital model of style in architectural design will operate we must first ask the following:

- What design properties or features adequately characterise style in terms of order and structure, as well as what classes of features can be identified to organise relationships with design requirements?
- What kind of measure will adequately compare design features and span concepts of complexity and similarity while allowing convergence in the society towards design categorisation and style recognition?
- What kind of computational model will demonstrate transformations of and within a style in a social design environment whilst addressing the role of local/ global utility and innovation?

2.2 Previous Approaches to Style

Within design, style is commonly used to describe consistencies among works that are the product of an individual, school, culture, period, or region. Studies on consistencies or patterns of objects and spatial features are a common approach to investigate and model design phenomena. Recent studies have worked within grammars and evolutionary design systems. Grammars and evolutionary systems are able to learn aspects of design by identifying shape grammars that define a product's style and use them to generate designs by combining patterns [Knight, 1994; Cha, 1998]. In this way rule-based systems have been used to reproduce design styles and combine rules defining different styles in order to generate a new design style.

Knowledge of procedural features has produced principles in many fields of design, including architecture where proportion and symmetry have been used to express consistent features. Implementations of a process view of style have been demonstrated by researchers [Ding & Gero, 1998; Cha, 1998] in studies on the knowledge of symmetry and proportion in buildings. Previous representations of procedural style approach processes at the level of the individual and are rules defined for the agent. This approach to process contains only explicit representations of individual processes that are generalizations inferred from the product.

A recent approach to establish a foundation for architectural design categorisation is based on information theoretic measures proposed by Gero and Kazakov [2001; 2002]. In developing a model of similarity and complexity measures for 2D drawings they were able to measure the information content of representations describing the design. The model compares both the similarity and the complexity of one drawing with other drawings. This information theoretic model is important for the development of a computational analysis of style. However much depends on the choice of features from which a measure of complexity and similarity can be derived. Features have extensively been used in geometric design assessment and categorisation, including architectural design [Meeran and Pratt, 1993; Brown et al., 1995; Tombre, 1995; Gero and Park, 2000].

In extending a feature-based approach to the analysis of style we focus on representing and comparing geometrical and topological features. Shapiro [1961], in his review of theories on style, considers that 'the constant form, and sometimes the constant elements, qualities and expression' are crucial to the characterisation of style. This description of style refers to two basic criteria that are significant to our approach: form elements and form relationships. Whatever is expressed within an architectural plan, whatever practical function it might serve and however it is constructed, the choice of form in design is constrained by what is geometrically and topologically possible [Steadman, 1983].

3. Digital Style Characterisation

This section outlines two general requirements for a digital characterisation that presents procedures for style recognition and categorisation.

3.1 Representation of 2D Drawings

In 2D design drawings there exists an interrelation between the whole and its parts, as well as the hierarchic scale of importance by which some structural features are more dominant than others. Order makes it possible to focus on what belongs together and what is segregated. However, arrangements outside the shape do not always reflect a shape's inner structure. Geometrical elements used to describe a shape transform due to the different relationships that are created by a shape's connections with other shapes. In other words, the shape structure remains constant yet the corresponding elements that previously defined the shape are transformed by the addition of another shape. Figure 1 illustrates some possible combinations for different types of connectivity for Shape **A**.

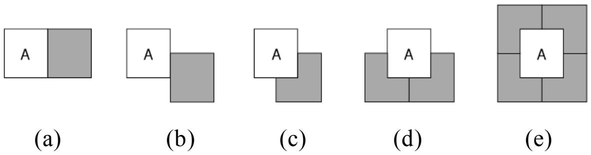


Figure 1. (a) Adjacent, (b) adjacent offset, (c) and (d) indentation or protrusion, and (e) surrounded

Shape **A** in Figure 1 maintains the same structural description of four adjacent right-angles. However when shape **A** is combined with one or more other shapes it produces: (a) a new description at the intersection and (b) additional intersections.

Representing and evaluating shapes in isolation does not carry sufficient information. It is not adequate to represent a shape only in terms of its internal structure it needs to be represented in relation to the organization, which it is a part of. The shape structure may be explicit and yet misleading, because its structure does not correspond to the arrangements embedded in its contours.

3.2 Framework for Digital Characterisation of Style

Recognition Procedure

A feature-based shape and space recognition procedure uses four discrete sequential processes. These processes are: graph generator/abstractor, shape/space encoder, feature detector, and feature classifier, and continues in three cycles until the original graph and its two abstracted graphs have been labelled, as shown in Figure 2.

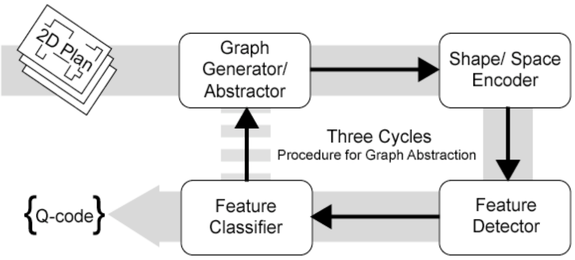


Figure 2. Feature-based shape and space analysis procedure

Data for each process are qualitative shape and space representations based on an extension of Q-codes [Gero and Park, 1997]. The qualitative encoding schema we have developed converts shapes and their relationships into a qualitative representation. These Q-codes encapsulate shape and space characteristics in terms of the nature of line intersection for rectilinear shapes and the adjacency of regions for rectilinear polyline shapes.

The shape and space encoder takes a drawing and transforms it into a syntactic representation using the encoding scheme. The feature detector takes this syntactic representation and searches for shape and spatial features that are identified in the form of structures in the representation. These structures include both primary and secondary semantics and include *indentation*, *protrusion*, *iteration*, *alternation*, and *symmetry*. The feature classifier takes the shape and spatial features and organizes them into sets. The second cycle uses the dual of the drawing and locates one other vertex within the external region or background of the drawing. This graph is labelled, encoded and sequenced [Kaufmann, 1984]. The sequenced spatial graph can now be labelled with the graph's vertices and arcs from the feature symbols derived from the plan graph to create a new semantic net graph. Information concerning the topology can then be obtained.

When more abstract features are identified on the basis of current available features, then a new representation on the basis of these new features is produced. The result is a series of semantic graphs that are qualitative re-representations of the original design drawing that describe both the drawing's geometry and topology. The resulting three symbol strings and their structure are canonical representations of the original design drawing.

Categorisation Procedure

Entropy measures have been applied to art and aesthetics [Attneave, 1959; Moles, 1966; Berlyne, 1971] and are utilised in our approach to computational analysis of architectural style. Entropy measures provide access to a rich source of data for the construction of a digital characterisation of style where variety, diversity, and differentiation are the target of generalisations.

The use of a feature-based representation makes it possible to estimate the structural information content of the three graphs, and consequently the information in the 2D drawing itself. Unlike the measures of selective information, entropy takes into account that the drawings features or feature classes occur with unequal frequencies. Our hypothesis is that the distributions of features parallel the intuitive notions of style in terms of its similarity and complexity by representing all possible diversity.

3.3 Feature-based Qualitative Representation

Drawings as Graphs

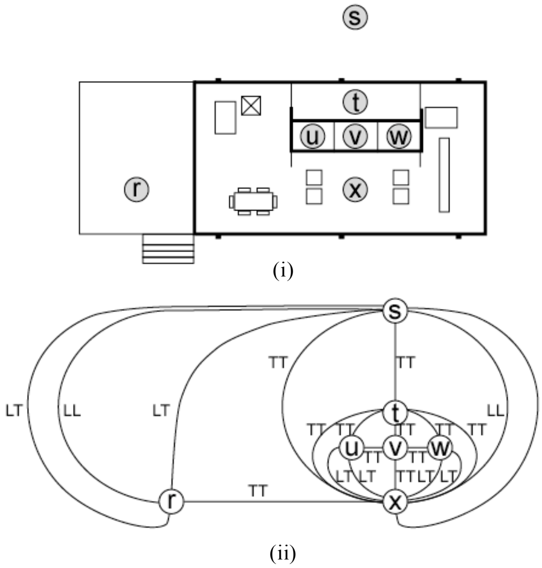
Shape and spatial features as classes are derivable from the intersection of line segments for bounded rectilinear polyline shapes [Gero and Jupp, 2003]. Taking the standard graph theoretic representation of shape contours we add intersection semantics to its vertices and arcs. This provides a description for shape features that are represented in terms of contour and position. The qualitative symbols or Q-codes define labels for various kinds of intersection of arcs for rectilinear shapes and their surrounding spaces. This method is applied to plan graphs.[1]

The positions of vertices in relation to the plan graph are described in terms of the order in which they appear in the graph. There are three kinds of intersection groups: ordinary groups, adjacent groups and enclosed groups, which respectively specify three kinds of topological structures by organizing vertices, shape contours and the overall graph in semantically different ways.

3.4 Semantic graphs

Semantic graphs are used to represent design knowledge in 2D drawings. By taking the graph theoretic representation and its intersection semantics we can produce a semantic network as the qualitative representation of the 2D plan drawing. From this representation we can then reason about the structures in the semantic network and their features.

The topology of 2D shapes can be represented as the vertex graph[2] of the plan graph and all spaces on the boundary are connected to an external vertex. For each arc in the new semantic graph we assign one of the five Q-code labels "L", "_", "T", "□", or "+". Each Q-code describes a different kind of orthogonal intersection that is produced by the connection of either two, three of four arcs in a plan graph. Each code corresponds to the labels given to the plan graph's vertices. Figure 3(ii) shows seven vertices, r, s, t, u, v, w and x (s is an external vertex), 20 arcs and 15 regions. Each arc is labelled by the Q-codes of the two vertices of the arc they cross in the plan graph as shown in Figure 3(i). We use this semantic graph to represent the sequence of Q-code encodings of a 2D design drawing, and to extract qualitative features by parsing this representation.



(i)

(ii)

Figure 3. (i) Original drawing (*Farnsworth House*), and (ii) semantic graph representation.

---

[1] A *plan graph* is a diagrammatic graph version of the plan itself.

[2] A *vertex graph* is a graph where spaces or 2D planes are represented by vertices and adjacent spaces connected by arcs.

The example chosen in Figure 3 is a 2D plan drawing of the Farnsworth House, designed and completed by Mies van der Rohe from 1946 to 1951. The Farnsworth house consists of two rectangular slabs floating above the ground shown in Figure 4.

Figure 4. Farnsworth House.

The continuous interior space of the house is delineated by an asymmetrically placed core volume, containing the kitchen, bathroom and fireplace and is a prominent icon of Modern Architecture in America.

Q-code Graph Analysis

The process of discovering visual patterns from drawings is called shape semantics and plays an important role in organising and providing order. Patterns that reflect basic shape features in terms of repetition and convexity, have been selected as they distinguish feature characteristics in syntactic patterns. There are five shape semantics identified: indentation, protrusion, iteration, alternation and symmetry. Iteration refers to a repetition of patterns with no interval; alternation refers to a repetition of patterns with regular or irregular intervals; and symmetry refers to a reflective arrangement of patterns (not necessarily expressed as visual symmetry).

We differentiate two classes of shape semantics. The first is a pattern of intersection relationships, which are represented explicitly and includes three of the five semantics: indentation, protrusion and iteration. The second is a pattern derived from the combination of shape contours that exists only implicitly in the relationships of a shape's connectivity derivable from the vertex graph and includes all five semantics.

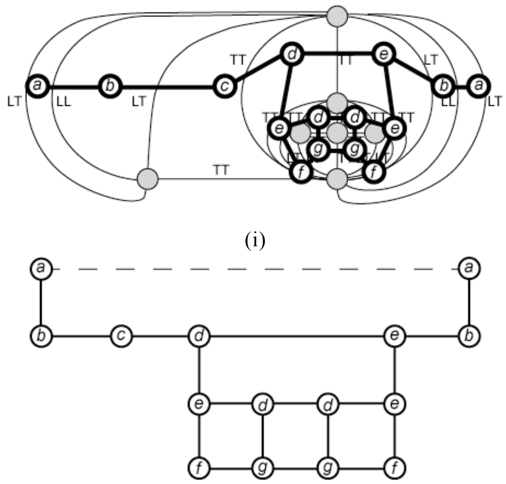
3.5 Vertex Graphs

The semantic graph is sequenced and labelled. Given the semantics of vertices it is now possible to re-represent the semantic graph in Figure 3(ii) as a vertex graph where vertices are the type of arcs in the semantic graph. In order to analyse the vertex graph model, semantic attributes are defined in order to interpret it [Gero and Jupp, 2002]. Table 1 shows the seven possible types of intersection for its arcs.

Table 1. Semantic Labels for Vertex Graphs

a	***b***	***c***	***d***	***e***	***f***	***g***
(L,L) □ (L,L)	(L,L) □ (L,T)	(L,T) □ (T,T)	(T,T) □ (T,T) □ (T,T)	(T,T) □ (T,T) □ (L,T)	(L, □) □ (_ ,T)	(T,T) □ (T,T) □ (_ ,T)

In our example, the seven different types of vertex are as shown in the graphs in Figure 5. The graph shown in dark lines in Figure 5(i) can be redrawn as shown in Figure 5(ii).



(i)

(ii)

Figure 5. Re-representing the semantic graph as a vertex graph.

In the encoding of 2D design drawings the interrelation between the whole and its parts, as well as the hierarchic scale of importance by which some structural features are more dominant than others can be found. In other words, wall intersections that are equal at one level of abstraction may assume a different level of importance at another level of abstraction.

This syntactic representation scheme enables the use of information theoretic measures on the Q-code string and graph structures. This offers us an investigation of aspects such as the average distance between two shape/space features, that is, the average minimum distance to be made from one arbitrary shape feature to another. As an alternative to working in feature space, we can represent this process from the feature space onto the space of the distributions in the feature space.

4 Applying Information Theoretic Measures to Semantic Graphs

The objective is to present a model that differentiates between 2D drawings and explicates the hierarchy of elements that comprise the artefact. In this way it is possible to create a formal computational measure of the artefact for what follows.

An information theoretic approach to the estimation of similarity and complexity is applicable to representations of qualitative graph-based forms with discrete alphabet labels. Once a drawing is encoded in this canonical form it is possible to measure symbols strings and the graph structures that represent them. The drawing's complexity can be defined by the amount of information within the Q-code string and graph structure. The similarity between the architectural plan drawings can be defined as the degree of similarity between statistical models. This section draws on the work of Gero and Kazakov [2001] on their applications of information theoretic measures.

4.1 Similarity Measures for Drawings

Shannon entropy is based on a simple statistical model of data, which assumes that they are generated by an ergodic Markov source, symbol after symbol in the simplest case and feature after feature in the more general case. The features can be either the Q-code strings or structural regularity in the graph data. For example if we have two different groups of design drawings (two different corpuses of work) that are encoded, their comparison can be carried out by constructing a Markov model for each group and computing cross entropy for each as:

$$\mathrm{En} = -\sum_{i,j} \mathrm{P}_T(q_i, q_j) \log \mathrm{Prob}_M(q_i, q_j),$$

where $\mathrm{P}_T(q_i, q_j)$ is the empirical probability of the symbol q_i following q_j in the other string.

4.2 Complexity Measures for Drawings

Entropy is an ensemble-based measure that is calculated for an ensemble of similar (generated by the same source) sequences. The complexities of the symbol strings are calculated from the vertices' components taken by the connections. Conditional probabilities are estimated from a sample of Q-codes text. Those that have higher entropy values, are treated as more complex than the ones with the lower values of entropy.

Structural diversity measures operate by constructing a finite probability schema by partitioning the N elements of graph structure into k equivalent classes of N_k equivalent elements according to a specified equivalence relation *E*. Here, p_i, $= N_i / N$ is the probability of a random chosen element belonging to the class *i* having elements N_i , and $N = \sum N_i$ The structural information content is then defined as:

$$I(E) = -\sum_{1}^{k} p_i \log_2(p_i)$$

Equivalence relations for calculating the structural information content are based on vertex graph equivalences. In the simplest case the vertex labels of the plan graph determine this equivalence and then semantic graphs can be employed. The combined structural information measure based on a number of different equivalence relations can then be used [Gero and Kazakov, 2002].

$$I_{combined} = -\sum_{j} w_j I(E_j), \sum_{j} w_j = 1$$

where w_i, are non-negative weights.

The development and implementation of similarity and complexity measures of 2D architectural drawings is used to formalise the measurement of the style of a designer. Further, the measures can be used to examine the change in complexity of drawings of designs of designer over time. They can also be used to compare the works of different design agents based on their complexities. What has been developed in the work of Gero and Kazakov can also be viewed as a descriptor that allows authentication of designed shapes generated by a particular designer, architect, school of architects, and ultimately style of architecture (Gero and Kazakov, 2001). This method is based on building a statistical model of a "typical" encoded design object and on using this model to construct an information theoretic functional with the desired descriptive properties. The tools, which are based on this method, can be used not only for the analysis of existing designs but also for generative purposes as a evaluator in conjunction with a generative system, which provides this system with a feedback and directs it into the subspace of design space where the designs similar to the targeted one are located.

The remainder of the paper describes social networks as the basis of an understanding of style relative to geometrical and topological relationships and social determinants for designing.

5 Exploring a Social Perspective of Style

Designers work with their situation, that is, their experiences, knowledge and conception, in order to determine the variables that contribute to the design. Particular variables are chosen *a priori* and are produced in response to the various situations that are encountered by the designer [Gero, 1998]. The design process used by a designer is unknown unless specifically revealed by the designer. Procedural features cannot be directly derived from the physical or informational artefact and these design processes are not static. Existing process models, which infer processes from the artefact based on reinterpretation do not allow emergent representations to be learnt and evolved in relation to the design situation. In the final part of this paper we ask: what can we do to improve our understanding of design processes in order to unify this aspect of style with the design artefact?

Social networks present an opportunity to explore this kind of problem, and have been studied elsewhere in understanding the patterning of individuals interaction. Social networks offer an understanding of systems made up of interdependent parts and their analysis is based on an intuitive notion that these patterns of interaction are important features. We believe that individual's design processes depend on how that individual is connected to the design community.

5.1 Insights from Social Networks

A central focus of social networks that supports our approach to style is the dynamics of distributed networks; that is, networks in which there is no centralized controller. This reflects how we may model style since within design practice changes in the design artefact and subsequent stylistic transformations occur via the interaction of many designers – even working on different elements of the design. Further, once a style has been recognized this tends to cause innovations to occur incrementally. In cases where significant changes in style occur, such as the transformation between modernist and postmodernist architecture[3] it makes clear that many important transformations involve innovative design, radically new requirements and unfamiliar design spaces.

In such a system, emergence plays an important role. Emergence refers to deriving global functions, behaviours, or structures from the local interaction among parts [Crutchfield and Mitchell, 1994]. The mechanics underlying the incremental changes in design and potential transformations of style therefore rely upon the interactions between designer, designs and context. A situated approach provides the basis for investigating the affects of design activity and interactivity on the transmission of styles among designers, incremental changes in the design artefact, as well as complete stylistic transformations.

5.2 Agent-based Social Networks

Designing in architecture occurs as the result of multiple designers (representing a group of individuals, teams or school), each potentially capable of proposing values for design features and requirements and evaluating these choices from their own particular perspective (e.g. desires, knowledge etc.). According to these evaluations design artefacts can then be ordered and arranged to establish a larger network of relationships between successive designs, revealing features that capture the structural and organisational relations of style.

Simulating a design society is based on a network composed of interacting design agents. The most obvious way to use agents is to assign one agent to each design participant involved. Predefined design requirements and qualitative features described in part one can be utilised in the synthesis of 2D spatial layouts. It is straightforward to map this model onto a network. We can map designers onto nodes, where each agent tries to maximize the utility of the design whilst operating within its style subspace. All the possibilities of feature-based representation and its associated values for requirement-based specification produce the design space.

A design agent perceives 2D design drawings using sensors and interprets it based on its geometrical and topological features. In this way agents are able to perceive the drawing as an ordered collection of qualitative features.

Figure 6 illustrates a simple model of design as a social network: where in the background figure the links between agents are illustrated as dotted lines; and in the foreground figure the small black circles represent either individual or classes of design features, the small white circles the design requirements, the links between them represent the inter-dependencies and the large ovals represent the style-subspaces (a subset of design artefacts) associated with each design agent.

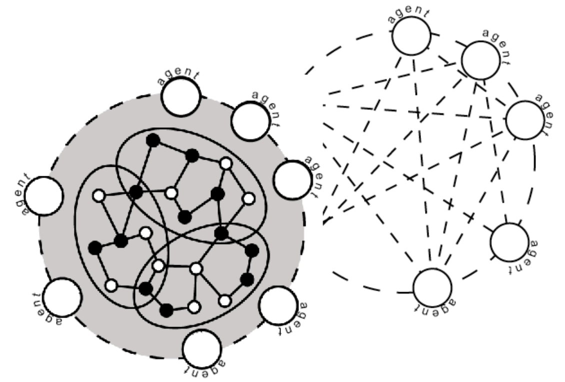


Figure 6. A simple model of the design space and style subspaces.

5.3 Style Transmission and Transformation

Stylistic transformations are time based. Recognition of style is not instantaneous after the design has been produced. Interdependencies between design requirements and design properties necessitate a phase of convergence (general agreement) satisfying dependencies acceptable to the design society. Emergence plays an important role in the transformation of style and consequently their transmission.

There are two means by which a society of design agents can transform style: by innovation and by imitation. Shape and spatial features on a 2D grid can be created via the different interactions of design agents operating in a context that defines style subspaces within the design space. An individual agent may succeed in putting a new style into practice, or an agent may increase its efficiency by successfully copying another individual's style. In this way styles spread incrementally among individuals through innovative and imitative activities. The transformation of style is then determined by the dynamic interaction of innovations and imitations.

Modelling Product and Procedural Style

Saunders and Gero [2001] presented an extensive investigation into the role that search for novelty plays in the evolution of artworks. By studying the emergence of social structures during the creative development they

---

[3] Modernism emphasized functional planning and applied scientific methods to design as opposed to the postmodernism architecture that evolved, which contradicted it, combining new ideas with traditional forms in unexpected ways.

investigated the effects that the search for novelty has upon the process of generation. Our approach incorporates Saunders and Gero's insights into a systems view of design and modelling of design groups, from which in their experiments resulted in the emergence of design cliques.

Our approach to a model of socially situated design style consists of multiple agents within a single field conducting searches for 2D plans. For each 2D plan generated the agent must assess the style of the drawing by sensing its features. The sensed drawing's style may then be recognised using the information theoretic measure as a standard evaluator for the design society. In this way, individual agents are able to categorize each drawing sensed based on information theory.

Individual preferences determine each agent's interest of the drawing's style based on values and previous learning experiences. The agent uses the interest calculated for each drawing's style to determine what actions to take in terms of selecting other 2D plans. Agents then communicate particularly interesting morphologies to others within their style sub-space and with other subspaces. After sensing a 2D plan and recognising its style agents can then be requested to produce a new design.

In the social network, features selected from each class correspond to a style and occupy the sample space. In this way, every geometrical element and its topological counterparts possess one of a number of alternative features. For any particular drawing, the set from which each feature is chosen is defined and comprises the vocabulary within the style subspace. This does not imply that one feature cannot be part of two styles but that the measure of the features frequency of distribution within the subspace delimits this vocabulary.

The agent's categorisation of the design drawing biases its design process. Each agent operates using a set of rule-based processes which update with the perception of 2D plan. A design agent's processes both in terms of activity and knowledge carry with them notions of their 'applicability conditions' [Gero and Reffat, 2001], derived from the design situation. In this way, regularities within an agent's plan drawing form the basis to situate its knowledge and activity. Procedural features may be inferred in the context of design requirements. Knowledge of style may therefore be abstracted and learned from existing 2D plans. An inference can be made on a possible process (or rules) that could be used to produce the result. The subsequent design experiences of individual agents enable categorization of prior design experience, composing knowledge of the style and to an extent structuring design activity.

Variety and Influence

Saunders and Gero [2001] investigated the behaviour of groups of agents with incompatible interest levels defined as the hedonic function. The collection of agents was placed in the same social setting. The results appear to be the formation of cliques: groups of agents that communicate frequently amongst themselves but rarely acknowledge the creativity of agents outside the clique. As a consequence of the lack of communication between the groups the "style" of artworks produced by the two cliques also remained distinct. The formation of cliques in the experiment by Saunders and Gero are comparable to the style subspaces we have described. We believe that these style subspaces perform a specific function in transmitting information to other agents. A design agent produces a variation, which may or may not be selected by the agent, and the agent in turn will pass the selected variation to the subspace. Should a design agent break a dependency within the style subspace and be influenced by a link outside then a transformation has occurred. Depending on the style recognition schema this transformation will either be maintained by other links within the style subspace or form a unique style subspace. Stylistic transformations may therefore have a variety of patterns of socialization by which a given feature or set of features are transmitted that affect their implementation in addition the design requirements.

Variety may be greater in some style subspaces than in others due to differences in the available individual features, classes of features and their distribution. Consequently every shape and space feature in a design drawing can be allocated a value and measured on a scale in terms of its similarity and complexity. Our hypothesis is that there is interdependence between the selection of features for different class sets and that certain features will be more likely than others to be identified within particular styles. In this regime encouraging influence relationships and local search strategies become a primary tool [Epstein and Axtell, 1996].

A key factor determining social network dynamics is the nature of the influences between agents. A process of defining and evaluating different styles can reveal inter-node influences incrementally. It is easier to define the influences directly based on knowledge of design decision dependencies. Agents may know for example that spaces have to be non-overlapping physical geometries, that topologies must have compatible functional connections, and so on. Therefore care must be taken in defining these influences for the system.

The Role of Utility and Innovation

It is reasonable to model the utility of a style as the local utility achieved by each design agent in the subspace. Global behaviour emerges as a result of concurrent local actions. Each design agent in a network tries to select the value that optimises its own utility while maximizing its consistency with the influences from other agents.

The global utility from the network state is a function of local utilities and the degree to which all the influences are satisfied in each style subspace. The dynamics of such networks emerge as follows: since all nodes update their local state based on their current context, the choices they make may no longer be the best ones in the new context of node states, leading to the need for further changes [Bar-Yam, 1997].

The design requirements and values for transforming style are relatively unfamiliar, and it is unclear where to start to achieve a given set of design requirements. There may be multiple very different good solutions, and there may be good solutions may that are radically different than any that have been tried. Further, there may be tendencies to reduce innovation due to the incremental modification of existing designs in well-known (successful) styles rather than exploring radically different designs outside the solution space.

Common to some agent-based social networks, agents demonstrate greater loyalty to producing designs within a particular subspace with certain global optima. Design agents must be willing to explore alternatives that, at least initially, may appear much worse from their individual perspective than alternatives currently being implemented. In applying these concepts to a model of style, a design agent operating within a style subspace may have a tendency not to innovate or borrow from other agents belonging to different subspaces. Therefore an application of this model needs to produce incentives for globally helpful behaviour. Previously this has been achieved using interestingness and curiosity. Concepts related to innovative actions such as functions of interestingness and curiosity have been identified as integral to modelling such systems [Martindale, 1990; Saunders and Gero, 2001]. These studies have identified that the more novel a stimulus presents the more complex it will appear to be. This does not suggest complexity implies innovation nor does it evaluate whether innovation has occurred however high levels of complexity may increase the potential to innovate within a social network.

6 Discussion

Style as an ordering principle allows both individual products and processes to be structured and in a broad sense characterize phenomena within the social sciences [Knight, 1994]. Social networks allow such effects to be explored. This wide-ranging approach to style is comparable to style concepts espoused by Thomas Kuhn called ‘paradigms’ [1967]. Kuhn defines ‘paradigms’ as consisting of a prototypical set of model problems and solutions to them, and are essentially styles of scientific research. Conceived in this manner, style is a general approach of attacking problems, consisting of a set of theories, methods, beliefs or goals and solutions [Martindale, 1990].

The possibility of identifying an appropriate feature space then re-representing drawings in this space provides the opportunity to add another layer of reasoning to analysing style. The co-occurrence of feature classes in design drawings relies on the network structure whose properties can be analysed in depth using the approach we have outlined.

We believe that this perspective has the potential to provide insight into several aspects of architectural style including: its geometrical and topological dimensions; providing a language organization that may reflect changes within features, class sets and their distribution; and exploring a situated approach to the synthesis of style in relation to design processes.

Considering both form and social determinants of style allows us to analyse 2D architectural plans, the processes that generate them and their relationships with the design context. This perspective offers the potential to reveal possible relations within design processes that transforms design requirements into design properties. Experimentation with this approach to style will further our understanding of the role of style in design as an influential phenomenon in changing context, designs and the style itself.

Acknowledgements

This research has benefited from discussion with Rob Saunders. This research is supported by an Australian Postgraduate Award. Computing support is provided by the Key Centre of Design Computing and Cognition.

References

[Arnheim, 1993] Arnheim, R., Sketching and the psychology of design, *Design Issues*, **9** (2,), 5-21.

[Attneave, 1959] Attneave, F.D., Stochastic composition processes, *Journal of Aesthetics and Art Criticism*, **17**, 503-510.

[Bar - Yam, 1997] Bar-Yam, Y., *Dynamics of Complex Systems*, Addison-Wesley. Reading, MA.

[Berlyne, 1971] Berlyne, D.M., *Aesthetics and Psychobiology*, University of Toronto, Appleton Century Croft, Educational Division, New York.

[Brown, 1995] Brown, K. N., Sims Williams, J. H. and McMahon, C. A., Conceptual geometric reasoning by the manipulation of models based on prototypes, *AIEDAM* **9**, 367-385.

[Cha, 1998] Cha, M.Y., *Architectural Shape Pattern Representation and Its Application for Design Computation*, PhD Thesis, University of Sydney, Sydney.

[Crutchfield and Mitchell, 1994] Crutchfield, J.P. and Mitchell, M., The evolution of emergence computation, Santa Fe Institute *Technical Institute Report 94-03012*, Sante Fe, NM.

[Ding, and Gero, 1998] Ding, L. and Gero, J. S. Emerging Chinese traditional architectural style using genetic engineering, in X. Huang, S. Yang and H. Wu (eds.), *International Conference on Artificial Intelligence for Engineering*, HUST Press, Wuhan, China, pp.493-498.

[Egenhofer and Shariff 1998] Egenhofer, M.J. and Shariff, A.R., Metric details for natural-language spatial relations, *ACM Transactions on Information Systems* **16** (4), 295-321.

[Epstein and Axtell, 1996] Epstein, J. M. and Axtell R. L., *Growing Artificial Societies: Social Science from the Bottom Up*, The Brookings Institution Press, Washington, D. C. & MIT Press, Cambridge, Massachusetts.

[Goodman, 1976] Goodman, N. *An Approach to a Theory of Symbols*. Hackett Publishing Company, Indianapolis.

[Gero, 1998] Gero, J.S. Conceptual designing as a sequence of situated acts, *in* I. Smith (ed.), *Artificial Intelligence in Structural Engineering*, Springer, Berlin, 165-177.

[Gero, 1996] Gero J.S., Cre ativity, emergence and evolution in design: concepts and framework, *Knowledge-Based Systems* **9**(7) 435-448.

[Gero and Jupp, 2003] Gero J.S. and Jupp J. Feature-based qual i-tative representations of plans, *CAADRIA03*. (to appear).

[Gero and Jupp, 2002] Gero J.S. and Jupp J. Measuring the information content of architectural plans, *in* PL Hippolyte and E Miralles (eds), *SIGraDi Caracas 2002,* Ediciones Universidad Central de Venezuela, Caracas, pp. 155-158.

[Gero and Kazakov 2002] Gero, J.S. and Kazakov, V., Modeling visual complexity of 3D solid objects, *Working Paper,* Key Centre of Design Computing and Cognition, University of Sydney, Sydney.

[Gero and Kazakov 2001] Gero, J.S. and Kazakov, V., Entropic similarity and complexity measures for architectural drawings, *in* JS Gero B Tversky and T Purcell (eds.), *Visual and Spatial Reasoning in Design II,* Key Centre of Design Computing and Cognition, University of Sydney, Sydney, pp. 147-161.

[Gero and Park 2000] Gero, J.S. and Park, S-H., Categorisation of shapes using shape features, *in* Gero, J.S. (ed.), *Artificial Intelligence in Design '00,* Kluwer, Dordrecht, pp. 203-223.

[Gero and Reffat 2001] Gero, J. S. and Reffat, R. Multiple representations as a platform for situated learning systems in design, *Knowledge-Based Systems*, **14** (7): 337-351.

[Kaufman, 1967] Kaufman, A., *Graphs, Dynamic Programming, and Finite Games*, Academic Press, New York.

[Knight, 1994] Knight, T.W., *Transformations in Design*, A formal approach to stylistic change and innovation in the visual arts, Cambridge University Press, Cambridge.

[Kuhn, 1967] Kuhn, T.S., *The Structure of Scientific Revolutions.*,University of Chicago Press, Chicago.

[Mantyla, 1988] Mantyla, M., *An Introduction to Solid Modelling,* Computer Science Press, Rockville.

[Martindale, 1990] Martindale, C., *The Clockwork Muse, The Predictability of Artistic Change,* Basic Books, New York.

[Meeran and Pratt, 1993] Meeran, S. and Pratt, M. J., Automated feature recognition from 2D drawings, *CAD* **25** (1), 7-17.

[Moles, 1966] Moles, A., *Information Theory and Esthetic Perception*, University of Illinois Press, Urbana.

[Saunders and Gero, 2001] Saunders, R and Gero, J.S., A curious design agent, *in* JS Gero, S Chase and M Rosenman(eds), *CAADRIA'01*, Key Centre of Design Computing and Cognition, University of Sydney, Sydney. pp. 345-350.

[Shapiro, 1961] Shapiro, M., Style, in Philipson, M. (ed.) *Aesthetics Today*, World Publishing, Cleveland, OH.

[Simon, 1975] Simon, H.A., Style in design, *in* Eastman, C (ed.), *Spatial Synthesis in Computer-Aided Building Design,* Applied Science, London, pp.287-309.

[Steadman, 1983] Steadman, *Architectural Morphology: An Introduction to the Geometry of Building Plans,* Pion,London .

[Tombre, 1995] Tombre, K., Graphics recognition general context and challenges, P*attern Recognition Letters,* **16**, 883-891.

This is a copy of the paper: Jupp, J and Gero, JS (2003) Towards computational analysis of style in architectural design, *IJCAI Workshop on Style* (to appear)