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Complexity through combination: an account of knitwear design

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Abstract

Designers immerse themselves in environments rich in inspiration. Previous research has tended to neglect the vital role of sources of inspiration in triggering and guiding designers' activities. This paper reports research which investigates the gathering of inspiration sources and exploration of ideas and hence attempts to understand how inspiration is harnessed. We conducted a progressive series of empirical studies looking at knitwear design: in situ observation; semi-structured interviews; constrained design tasks; and computational modelling. The paper proposes simple general accounts of observed design behaviour and shows how a simple parts-and-relations account can explicate aspects of subtlety and complexity in design.

Keywords: conceptual design; design cognition, design behaviour, design activity, computational model, complex systems and complexity

Complexity through combination: an account of knitwear design

Designers immerse themselves in environments rich in inspiration: collecting examples, amassing libraries, pinning notes and images around their workspaces, and so on. Yet, although there is broad recognition that much of design proceeds by modification of previous ideas, previous research has tended to neglect the vital role of *external sources of inspiration* in triggering and guiding designers' activities. It appears that most attempts at computer support and most research starts with conceptual design; this paper reports on research which attempts to investigate the even earlier gathering of sources of inspiration and exploration of ideas and hence to understand the mechanisms by which inspiration is harnessed.

The research focused on knitwear design as a good example of practical design — requiring designers to express artistic flair within pragmatic constraints in an environment driven by market and marketing pressures. The work examines how sources of inspiration (such as photographs, images, previous garments, art work, swatches, artefacts or natural objects) are gathered and transformed into practical designs, i.e., into commercially viable products. Current practice and 'received wisdom' are often based on myths and misunderstandings of the creative process [1,2]. An understanding of the mechanisms by which inspiration is harnessed is necessary for the development of better design environments (including appropriate computer support tools for designers) and for the improvement of design education.

The focal questions of the reported research were:

1. What is the nature of sources of inspiration, and how are they used?
2. Is there commonality of behaviour among designers in the early design process with respect to use of sources of inspiration?
3. Are there discernable design 'sub-processes' in common use?

The research was largely elicitative and descriptive and therefore combined methods in order to explore the use of sources of inspiration from different perspectives and hence enable triangulation. The questions were addressed in a progressive series of three empirical studies:

- i) targeted *in situ observation* and *semi-structured interviews* to understand design activities in their natural context (related to the "cognitive ethnography" characterised by Ball and Ormerod[3]); leading to
- ii) *constrained design tasks* in order to study the use of visual sources of inspiration by different designers in comparable settings, and using outcomes from those studies to derive cognitive accounts to guide
- iii) *computational modelling* of portions of the spatial abstraction and transformation processes, in order to assess the sufficiency of the emergent accounts of design behaviour.

This three-phase, multiple method approach allowed us limited verification of the findings. Inductive analysis was undertaken in order to derive accounts of this very early design activity from observed and reported behaviour. From the descriptive accounts, we proposed possible cognitive accounts of underlying reasoning, portions of which we implemented in computational models. This modelling allowed us to identify areas of design activity which could be explained simply (while not claiming that we have captured the exact mechanisms used by human designers).

This paper presents the results of the design studies. The next section justifies the choice of domain. The three phases of empirical study are described in turn, with methods, findings, and discussion presented for each. Finally, discussion and summary sections consider overall findings.

1 Why knitwear design?

Knitwear is an example of ‘practical design’ in a fast-moving and highly competitive manufacturing industry that makes both technical and aesthetic demands of the designer. It is a constrained, tractable design domain, typically involving individual designers designing independent, low-resolution, static artefacts. The fast design turn-around (driven by an annual cycle of fashion ‘seasons’) provides opportunities to observe the design cycle in a limited period. Because of technical and manufacturing factors and the need for effective hand-over from designer to technician, the mechanisms for realising design – for taking it from the conceptual stage through manufacture – are well-established (albeit little articulated) procedures. Knitwear designers have a cultural openness about what the sources of inspiration are, and so the sources, and their adaptation, are relatively accessible to external observation.

The nature of knitwear imposes particular design constraints, because the stitches are discrete, forming a relatively coarse matrix to support the colours and textures of the yarn which will produce the final pattern. The choice of yarn (i.e., its weight and texture) may introduce distortions into that matrix. Manufacturing constraints are also tight, because of physical limitations of yarns, technical considerations of the machine knitting process, low unit costs (and hence cost controls leading to limitations on yarns, numbers of colours, and even the development of new stitch patterns), and fast turn-around (with as many as six collections presented by a company in a single year). The design must be suitable to be knitted — and then suitable to be worn.

Hence, the use of sources of inspiration can involve a variety of transformations that can give insight into aspects of design reasoning. For example, the transformation from one form to another: transformation into a design motif typically requires transferral from a continuous medium (e.g., a continuous painting or photograph) to a ‘granulated’ form; transformation from a natural object requires translation from a three-dimensional object to an effectively ‘two-dimensional’ fabric; the low resolution of knitted fabric means that even the simplest transplantations of motifs tend to require some kind of abstraction or simplification. Many transformations require spatial reasoning.

Knitwear shares important characteristics with other design domains:

- typically involving external sources of ideas and re-use or re-interpretation of ideas,
- requiring consideration of technical constraints within the earliest design phases and throughout the design process,
- involving spatial reasoning in several interlocking problem spaces (e.g., the design of the motif or surface pattern — subject to the constraints of the knitwear matrix, the design of the fabric structure or stitch pattern — subject to

the constraints of the yarns and knitting machines, the design of the garment shape — subject to the constraints of the fabric and construction, especially with regard to knitted-in shaping),
- subject to market and marketing pressures.

The project sought, within the context of practical design, to identify and model the processes by which sources of inspiration are identified, assessed, and adapted. Knitwear was selected as an appropriate domain because it shares key similarities with other domains while including constraints that make it relatively accessible for study. Further, pragmatically, members of the project team had knowledge of the industry and access to expert designers in it.

2 Phase 1: Observation and interviews

2.1 Methodology for phase 1

In the first phase, knitwear designers at work in industry on real product lines were interviewed and observed, with particular attention to designers' source-gathering activities. This encompassed 18 companies involved in knitwear design in the UK, Italy, and Germany, plus one hand-knitting designer.

Observations – shadowing staff designers as they were available – were conducted over a number of days in 3 companies. In 2 of these 3 cases, it was possible both to follow particular designers at intervals throughout the period of observation and to follow a number of different designers for shorter periods. In the third case, a single designer was shadowed intensively over a two-week period. In addition, short observations (i.e., within a single day) were conducted in 3 other companies, each with additional time for interviews. Observations included watching people through the design process, listening to conversations among designers, and attending to the workspace and broader environment. The extent of observation was constrained by how much access was permitted by the companies; hence, it was determined pragmatically.

Semi-structured interviews were conducted in all 18 companies, often with more than one designer. The interviews focused on three areas:
- the general design process (including time, constraints, decision making)
- research activity and use of sources of inspiration
- use of materials (e.g., samples, boards, workspaces)

Data was collected in field notes, and using audio or video recordings and photographs where permitted. Some participants allowed us to gather design materials. Most of the data collection was done by Dr. Claudia Eckert, the project's Research Fellow, who is multi-lingual.

The observation and interview phase allowed us to collect examples of how designers behaved and how they reported their activity. It allowed us to see design activities in context, and to focus our questions and shape our subsequent design studies. Analysis was delayed until all data was collected, to help us avoid anticipating parallels and allow us to observe each company in its own terms. Analysis of the observation and interview data followed vectors of enquiry – that is, analysis focused on key issues about the nature, use, and adaptation of sources of inspiration. The intention was to understand the range of behaviour observed and to note patterns within it, to note interactions with the work environment, to examine the relationship between observed behaviour and reports, and to identify clues to phenomena requiring further investigation (such as reports of instantaneous whole designs, or transformation to a gridded design).

2.2 Findings from phase 1: observation and interviews

The research confirmed that there is discernible commonality within the individual variation in the early design process for knitwear, and that individual practices incorporate common patterns which can be codified. Knitwear design is rarely started from scratch, but design ideas are placed into the context of fashion through these sources of inspiration. Often, designs based on sources of inspiration are implemented through re-use of existing patterns which emulate the over-all effect (since re-use is cheaper than development of new structure patterns). Many dimensions of design — yarn, shape, colour, complexity of motif, fabric structure — are constrained by what is feasible and affordable to produce on knitting machines.

The patterns of behaviour we report were consistent through the interviews and through the observations (and they were corroborated subsequently by the constrained tasks, described below). Similar behaviours were seen in different contexts, both in short visits and in the longer observations. Sometimes, activities mentioned in interviews or during short visits were observed in the more intensive sessions, so that there was considerable comparability of behaviour and report. The transition from source of inspiration to its interpretation in a design is something that typically happens quickly, and so was observable both in shorter and longer visits.

This consistency and the breadth of the interview coverage give us confidence in the representativeness of the observations, even though (for pragmatic reasons) they were not as extensive as we would have wished.

2.2.1 Sources of inspiration

Designers immerse themselves in environments rich in inspiration: collecting examples, amassing libraries, pinning notes and images around their workspaces, and so on. They engage in a continual search for and collection of sources of inspiration (despite that they often do so without management recognition or support). The sorts of sources observed in use by professionals, include:

- **other garments** from market leaders and competitors, from their own past collections, and from history.
- **representations of garments**, including sketches, photographs, descriptions, and patterns. Designers study trend forecasting materials, trade literature and fashion magazines.
- **materials**, such as yarns and fabric samples, and **other textiles**.

- **art works**, such as paintings, drawings, sculptures, and photographs, and representations of them.
- **artefacts from other domains**, such as tins of baked beans, especially craft designs and objects with repeating patterns such as mosaics, but extending to buildings and commercial objects. Also representations of artefacts.
- **natural phenomena and objects**, such as sunsets and leaves, and representations of them.

The use of sources of inspiration was observed in all companies and all designers.

2.2.2 Designers' design research

Each design season begins with design research [4]. During the research stage, designers set the context for the garments to be designed, setting a theme, selecting yarns, and designing colour palettes (typically 5 to 7 colours). Setting context is heavily influenced by fashion forecasts and customer profiles. Once the 'look and feel' are sketched out through themes, yarns, and colour palettes, designers produce a 'design framework' which specifies which garments a collection will contain: numbers of garments, types of design, styles and proportions.

For example, a nautical theme might be reflected in a 'mood board' that includes a lighthouse and boat watercolour, some fabric swatches and paint chips reflecting colours selected from the watercolour, some yarn and cord samples, and some photographs of fishermen at work and of boats. The 'look and feel' might be characterised by selected colours and yarns that derive from the 'mood board'. The corresponding collection might include specified numbers of men's and women's cardigans and pull-overs, some single-colour with specified textures, some plain-knit with multiple colours and motifs; including variations in neckline and details (such as pockets and buttons), all loosely proportioned.

2.2.3 Use of sources

Designers use sources of inspiration primarily to plan the conceptual design of a future season's collection, or for relatively direct translation into a particular garment design (e.g., a patterned cardigan intended for a male golfer). Different, even disparate, sources can be combined in one garment. Designers use sources of inspiration to serve different functions in the design process:

- they provide a **context for the fashion** to be designed, bringing into play awareness of the external physical and social environment (e.g., austerity tailoring in war-time), of fashion trends in general (e.g., 'Annie Hall' and 'grunge' were pervasive styles), and of broad themes that might shape a collection (e.g., military dress, or 'flower power');
- they provide **information** about the ranges and capabilities of competitors, by providing examples of styling and design, trade-offs between materials and pricing, and use of manufacturing technologies;
- they are used as the **source of features**, such as necklines or proportions;
- they provide a **basis for adaptation** for detailed designs, suggesting elements, features, and ideas that can be incorporated into a particular design (e.g., reflecting a nautical theme in an anchor pocket motif);

- they provide a **means of conveying** design ideas by making reference to the source, that is, designers point to examples to explain what they mean, e.g., pointing to a physical garment to indicate a detail of construction.

2.2.4 Visualisation

Interviews suggest that designers rely heavily on mental visualisations of designs. Many designers report mental images which they perceive as 'complete' designs, typically as worn on a human body. The perception of 'completeness' may be misleading; elaboration of these images often includes indeterminacies and variabilities. It appears that they can visualise fabric pieces accurately in their minds, and that they explore options through visualisation. They can answer questions from their mental images (e.g., does it have a peplum or not?), and they describe altering aspects of their images (e.g., revising a neckline or sleeve length) and focusing on details (e.g., how many buttons). Their images can include colour and texture.

2.2.5 Sketching

Sketching is also crucial. The nature of the sketching activity suggests that it is both expressive and reflective: often designers sketch quickly and without hesitation, erasing little; sometimes they confirm lines by going over them repeatedly, tidying the sketch without adding information. Designers normally work on one part of the design at a time (e.g., border, then central motif). They appear to hold only a small number of features in mind at any one time, and then select new ones at need. Sometimes they study the source before each design. Often they go straight to the next design without any delay. This dual function is corroborated by the designers' self-reports; they talk about "getting it down" and also about evaluating balances of colour and pattern based on sketches. Many designers mentioned using a knitwear computer-aided design (CAD) system to 'sketch' in a comparable way.

2.2.6 Designs in communication

Designers often discuss designs by reference and analogy to previous designs — so that sources of inspiration provide a sort of "index of communication". In other words, the labelled designs themselves contribute to a design description language based on reference. At each stage of the knitwear design process, designers may refer explicitly to sources of inspiration to capture and communicate their design intentions (e.g., to other designers, to buyers, to technicians, to clients). For example, theme boards often contain sources of inspiration (e.g., images, artefacts) to help convey the 'feel' or unifying idea. Design frameworks may be conveyed through design sketches, swatches, yarn samples, and clippings of previous garments or designs. Designers sometimes rationalise the inspiration process for marketing presentations.

2.3 Phase 1 discussion

We undertook an inductive analysis of the designers' self-reports, identifying commonalities and regularities, and distilling design processes. The next session describes four accounts of design processes emerging from that analysis. The subsequent section then relates these accounts to observed design behaviour. Finally, the accounts are related to other notions and models in the literature.

2.3.1 Four possible accounts from designers' reports

Working from the designers' reports of their design processes, we derived four possible accounts of their design processes (including use of sources of inspiration):

i) **the holistic account**, that designers produce whole designs conceived instantaneously in reaction to a source of inspiration; the visualised garment is experienced subjectively as a complete design, although details may not be fully resolved.

ii) **the decision cascade account**, in which the design emerges from the processes enacted as the consequence of a sequence of decisions, or decision cascade: decisions (which initiate design procedures) have consequences constraining and requiring subsequent decisions, etc.

iii) **the goal-and-cliché account**, that designers decide on high-level goals which are realised through a series of design clichés (i.e., schemas or templates), and that the clichés in turn influence the decision space.

iv) **the plan and procedure account**, that designers make a high-level plan (e.g., key structural decisions) and then fill in the details through a series of design procedures (encompassing goal, selection, and realisation, e.g., "to make a border,...") or clichés.

The last three accounts (which we'll call the 'decision sequence accounts') have much in common (in each, early decisions change the context for subsequent decisions), but are distinguished for this discussion in order to highlight their distinct emphases: the decision cascade account is a sequence that emphasises increasing constraint without working from an overall plan or goal; in the goal and cliché account, design is driven by a hierarchical goal structure: as known design solutions are associated with goals, new sub-goals may be generated or the goal-structure adjusted; the plan and procedure account is plan- (rather than goal-) driven, and the plan is elaborated by design procedures (or heuristics) as well as by implementation of known solutions.

The 'odd one out' is the holistic account, which is included because some designers reported that complete designs appear instantly in their minds when they see sources of inspiration. This description has similarities with the 'aha!' phenomenon investigated by Akin and Akin[5] among others, who highlight the fact that what they call a 'sudden mental insight' does not arise from nothing, but from certain preparation which creates the conditions conducive to creativity. Hence, apparently 'instant' design relies on earlier mental preparation.

We speculate that, in their continual collection of sources of inspiration, designers are building repertoires. It seems plausible that they are analysing and designing as they are gathering: responding to the sources and mentally building 'stubs' or partial designs, classifying examples and associating them with other material of that class, toying with design ideas even when they are not working on a particular collection. These 'stubs' may be added to the designer's repertoire of 'clichés'. This is corroborated by many designers' own accounts. Hence the 'holistic account' can be understood as analogous to Japanese brush-stroke painting, in which considerable mental preparation and contemplation are externalised in a fluid, almost instantaneous rendering.

This speculation re-casts and de-mystifies the holistic account in a way that has more evident similarity to the other accounts that associate existing design solutions and ideas with goals or plans. Both the goal-and-cliché account and the plans and procedures account may be understood as drawing on a repertoire derived in part from analysis of sources of inspiration.

2.3.2 Relating these accounts to observed designer behaviour

These accounts are based on what designers *report* of their experiences and thinking through the early design process. There were indicators in the observations of their behaviour that are consistent with each – but the collection of observed indicators were not all consistent with any one account. Typically, a given design example showed indications consistent with more than one account. So, it appears that any one designer employs more than one strategy, and that multiple strategies may be employed within a single design example.

For example, designers often sketch quickly and without hesitation, suggesting that they are externalising a design which they hold ‘whole’ in their minds – they talk about “getting it down”. This is consistent with the holistic account, but it is also consistent with the goal and cliché account.

Designers normally work on one part of the design at a time (e.g., border, then central motif). This is consistent with the three ‘decision sequence accounts’, where the initial selection of focus (the choice of which part to work on) may be arbitrary, goal-driven, or plan-driven. It emphasises that much design is focused on simple decisions in a context of previous choices. Designers appear to hold only a small number of features in mind at any one time, then select new ones at need. Again, this is consistent with the three ‘decision sequence accounts’ – and inconsistent with the holistic account.

Designers talk about evaluating balances of colour and pattern based on sketches. The use of iterative evaluation supports a ‘decision sequence account’, especially the decision cascade account.

In summary, the findings highlight certain aspects about the design process:

- At many points in a sequence of design decisions (i.e., a design process), the decisions are simple ones, concerning a limited focus on particular features.
- Each design decision contributes to a developing context for the subsequent design decisions, and designers display sensitivity to this developing context.
- There is evidence that designers use and make reference to known solutions, that they draw on a repertoire developed through experience and exposure to other sources.
- Much design is incremental and iterative, with a cycle of decisions (many of them of limited focus) and the evaluation of their impact.

2.3.3 Relating these accounts to other design literature

Models of design
Many models have been proposed of the design process (see Cross[6] for an overview). Of these, one of the simplest is shown in Figure 1. The general idea in all of these models is that the design follows an iterative process of generation and modification – as we, too, have observed – until it is evaluated as being satisfactory, after which it can be communicated to those who will fabricate the object. This is consistent with both reported and observed behaviour in this study. The model admits the notion of partial instantiation, allowing a design to develop from an initial conceptual scheme (with few details of the parts or even their precise relations) through gradual or part-wise instantiation as design decisions are made. We observed design behaviour consistent with this model: designers appear to hold only a small number of features in mind at any one time, selecting additional features or re-focussing their attention at need; and designers tend to work on part of the design at a time. The emergent decision sequence accounts, based on designer self-report and clarified through observation of designer behaviour, are compatible with this model of the design process.

Figure 1 A simple process model of design

Cognitive perspectives
The emergent decision sequence accounts also map onto existing cognitive perspectives on design activity and sub-processes. Those perspectives are themselves based on empirical investigations in a variety of design domains. Hence, notions of ‘plan’, ‘procedure’, and ‘cliché’ used in our emergent accounts follow usage in other domains (e.g., in software design [7]).
Bartlett [8] suggested that memory takes the form of schemata which provide a mental framework for understanding and remembering. In general, the term ‘schema’ is used to indicate a form of mental template which organises cognitive activity such as memory, reasoning, or behaviour. Key characteristics or elements in the schema have ‘slots’ in the mental template: the slots represent the range of values acceptable for those key characteristics. Schemata may be of varying levels of complexity and abstraction; their importance is in providing structure and economy.

Hence, our ‘procedures’ and ‘clichés’ may be understood as schemata. The decision sequence accounts concern how schemata are accessed and employed during the design process. Simon [9] observes that, when a task is ill-defined, users resort to pre-existing concepts: stereotypes, schemata, or other knowledge. Cole and Kuhlthau [10] see the use of schemata as fundamental to sense-making at the outset of problem solving: the problem-solver invokes a schema or model of the problem in order to create a frame of reference and hence to identify the initial problem state. We have seen that designers draw on sources of inspiration to help structure the problem and establish an overall strategy. The emergent decision sequence accounts embody strategies that can be understood as successive employment of design schemata.

Mental imagery
Self-report suggests that designers rely heavily on mental imagery incorporating indeterminacies and variability as well as the abilities to manipulate design components

and to alter mental focus. Selection of focus appears to be an important mechanism: designers appear to work on one part of the design at a time and to focus on a small subset of features. Designers appear to be able to visualise past designs readily and hence to draw them into their mental design imagery.

Logie [11] provides an explanation of how this might be achieved. He describes an economy of images in memory, through which access to previously unrelated bits of information might be achieved: many informative elements are integrated together in a structural whole, increasing the available amount of information in working memory. Hence remembered rich images are encoded in some way, so that they can be referred to economically. The resultant juxtaposition of the *rich* images in mental imagery can generate new associations and insights.

In this way, mental imagery is associated with insight. For example, Anderson and Helstrup [12] argue that mental imagery is a source of discovery and synthesis. Bartlett [13] wrote that imagery leads into bypaths of discovery.

Shared referents
Logie's notion might also help to illuminate the observed use of sources of inspiration – of images – as an index of communication. The use of images as referents allows designers to index into rich visual memory. The labelling of those images or referents allows designers to externalise their associations and to communicate them to other designers, turning them into *shared* referents. Meaningful discourse requires shared referents. Using sources of inspiration as an index of communication is a mechanism by which shared referents can be established.

3 Phase 2: Constrained design tasks

3.1 Methodology for phase 2

The second phase focused on designers performing realistic but constrained design tasks with supplied resources. It aimed to gather evidence on the use of sketching, on decision sequences, on spatial manipulation and reasoning, and on mental imagery. The tasks were constrained in a way that removed some design considerations (like shape design) while preserving realistic complexity of others (like motif design) — hence facilitating our identification of abstraction and transformation activities. This is not unrealistic; for example, designers at company M[1] design with just such a separation, first creating the Jacquard pattern[2] for the fabric without regard to shape, and then designing the shape using the patterned fabric.

Designers talked aloud during the tasks after concurrent verbalisation instruction and practice. The sessions were videotaped from two angles, in order to capture the

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[1] Designations used in this paper have been anonymised to preserve the confidentiality of the participating companies.

[2] Jacquard is "a fabric in which the design is incorporated into the weave instead of being printed or dyed on" Collins Dictionary of the English Language, second edition, 1986

designers' actions and gestures in the environment, and to capture their handling of the materials when scanning and sketching. All of the products of the design process (e.g., sketches, samples, mood boards) were collected in the sequence in which they were produced. Each designer was interviewed after the design tasks, including some review of the videotaped session; we were interested in eliciting their phenomenological perceptions of their design processes.

Figure 2 A simple garment shape

Figure 3 The Persian carpet used as a source of inspiration

Figure 4 The William Morris wall hanging used as a source of inspiration

The design task was to produce one or more sketched sweater designs (to any level of finish) for a prescribed, simple shape (see Figure 2, i.e., to produce designs for the motif or surface pattern) from given source. The task was performed with two different sources: a photograph of a Persian carpet (Figure 3) and a print of a William Morris wall hanging design (Figure 4). The sources were chosen to be different from each other in style in order both to accommodate differences in designers' own preferences, and to mitigate against bias arising from the source. The sources were chosen to mimic sources observed in use by designers and to provide sufficient richness to inspire a variety of designs. Designers were given about 30 minutes for each source. This was largely an elicitation exercise, aimed at gathering information about:

a) selection and manipulation actions observed in the transformation from source to product (to be gathered into an informal 'catalogue'),
b) decision sequences (in order to plot the 'trajectory' of selection, decision, and action), and
c) mental imagery (from which we hoped to elicit some indication of how complete and detailed designers' mental images of designs are).

The study was conducted with three cohorts:

i) 11 professional knitwear designers from various companies (our focal group);
ii) 9 M.Sc. knitwear design students (allowing us to make some comparison between their behaviour and that of professional designers; note that such students typically have industrial experience of tasks of this sort through placement schemes or prior experience);
iii) 4 non-designers (used as pilot subjects and to provide some insight into the significance of design education and experience).

The rationale for this approach is to gather as much information as possible from the co-operating professional designers without imposing too great a burden on their time or patience – i.e., within the time they allowed us.

Tapes of the constrained design tasks were transcribed and subsequently encoded in a variety of ways. Design elements selected from the sources were catalogued. Placement schemes (of design elements within the garment outline) were catalogued. Design actions and decision actions were catalogued. Initial analysis was in this way data driven, in order to identify a coding protocol to support the studies' foci. Transcripts were then annotated in accordance with the resultant coding protocol. The annotated transcripts relate time-stamped verbalisations to design actions and to interactions with sources and sketches. This annotation supports examination of action sequences and interactions. Analysis was then enquiry-driven.

3.2 Findings from phase two: constrained design tasks

Designers incorporate elements or ideas from sources of inspiration into their detailed designs using various strategies, addressing three sorts of design decisions:

- selection (choosing elements for use),
- adaptation (interpreting selected elements), and
- transformation (manipulating the selected and interpreted elements spatially within the particular composition).

Designers intermix these strategies fluidly, in no particular sequence. Strategies associated with each sort are elaborated below.

3.2.1 Selection strategies:

The analysis (an earlier version is presented in Eckert [14]) reveals a variety of selection strategies by which designers identify elements in the source and select them for transformation and placement onto the design. For example:

- **selection of interesting features** (source-driven): The designer picks interesting features from the source and look for opportunities to use them in the design. Features may include design elements (e.g., motifs, shapes, patterns), colours, relationships (e.g., combinations, proportions, juxtapositions, spacing).
- **mirroring using salience priority** (source-driven): The designer puts the most salient feature from the source onto the garment in a similar role (e.g., a central motif). Then the designer seeks other features in the source that complement that usage, often continuing to echo the configuration in the source (e.g., taking a diamond shape from the source in Figure 3 as the central motif, and scattering smaller horse shapes around it).
- **essence extraction** (source-driven): The designer analyses the source for its key characteristic elements (e.g., complex borders) and relationships (e.g., proportions or combinations) and then tries to express these in the design, possibly translating them into traditional patterns or interpreting them as stitch structures.
- **instantiation of class** (design-driven): Designers have in mind a class of usage, for example a portion of the layout (such as an overall pattern or a border) or a structure (e.g., an intarsia panel) and look in the source for suitable design elements to fulfil that class. This is like ‘filling in gaps’: ‘I have this class of usage, and I need ‘one of these kinds of elements’ to fill it’. When the design nears completion, this sort of selection may indeed be ‘gap-filling’.
- **role fulfilment** (design-driven): This is similar to instantiation of class, but reflects attention to aesthetics or ‘feel’ of the design, rather than to the layout. The designer seeks design elements that fulfil an aesthetic role in the design, e.g., providing contrast with other features, adding colour, adding ‘life’.

- **realisation of concept** (concept-driven): The designer selects design elements and relationships which reflect the essence of a concept or theme, e.g., the crucial or 'signature' constituents of Arts and Crafts style.

3.2.2 Kinds of adaptation

The analysis [14] identified kinds of adaptation executed by the designers (see Figure 5 a-f for examples):

- **literal**: No adaptation is intended; the source element is copied as directly as possible into the design (although the constraints on knitted fabric usually entail some simplification or change of resolution).
- **simplification**: Deliberate simplification, e.g., to reduce the number of colours or the complexity of detail; selection of some details and omission of others.
- **abstraction**, leading to a design which captures the essence of the source, but not the specific elements. The abstraction may maintain key visual properties of the source or may retain only abstract properties (e.g., complexity, relationships, pattern structure).
- **modification** or variation through re-arrangement, replacement, or re-combination of elements, or through introduction of other material.
- **association** with other elements or ideas which are visually similar, which originate in a similar context, which have similar properties in a different context, or which remind the designer of related ideas.
- **deviation** to completely different sources which are in the designer's current context or on their minds.

Figure 5 Designers' designs: examples of the kinds of adaptation executed by designers.

Human strategies for creative design which are similar to those observed in our constrained tasks have been identified and discussed by others. For example, Rosenman and Gero [15], in their discussion about the use of prototypes in creative design, suggest two basic approaches to creating new structural elements. One – not mirrored in our observations – is 'building from first principles', creating a design from basic 'building blocks'. The other is to build on previous designs and modify them using any of three creative design processes:

- combination (bringing elements from previous designs and combining them in novel ways to create a new design)
- mutation (modification of the structure of a single existing element) and
- analogy (generalising through functional attributes to artefacts outside the current domain).

Our observed adaptations have similarities to these processes. Simplification is a form of design by mutation. Association and deviation are forms of design by analogy, although the association may not be based on functional attributes but on aesthetic notions or on experiential resonances (that may seem arbitrary to an observer). Modification includes some design by mutation but, since it may involve introduction of other material, it also relates to design by analogy. The purpose of both abstraction and literal is not to produce a new structure but simply to transport the source of inspiration to the knitted garment and so falls outside Rosenman and Gero's description.

Gero [16] identifies an additional creative design process – emergence – whereby new, previously unrecognised properties are perceived in an existing design. Cross, too, uses all four of these processes in his analysis of the 'creative leap' in the design of a bicycle luggage rack [17]. Emergence was not explicit in the observed adaptations, but it could be implicit in any of them except literal. What the designers are identifying to extract and adapt may be an emergent property.

3.2.3 Transformation mechanisms

The transformation mechanisms identified are familiar forms of spatial manipulation (like those available in most drawing programs):

- translation (moving to another position)
- reflection (mirroring)
- rotation (turning around a point)
- scaling (changing size proportionately)
- attenuation or other distortion (e.g., stretching, twisting)
- truncation (cutting off a part or edge)

These are augmented by repetition and combination — sometimes producing 'emergence'.

The findings suggest that the source-to-design transformation process uses a repertoire of relatively few, simple mechanisms for selecting and adapting design elements from inspirational sources.

3.3 Discussion of phase 2 – a combinatorial account based on 'parts' and 'relations'

From the activities we saw designers conduct and describe in phase 2, we identified strategies of selection, adaptation, and transformation. These are collections of simple strategies of limited scope. These simple strategies, when used in combination, can produce complex and sophisticated designs – and designer behaviour. Further, we see that these strategies combine, through their successive or combined application, to produce a developing context within a given garment design.

From these findings, we derive an account of the design activity observed in phase 2 that encompasses these strategies and suggests how some of the observed complexity results: a combinatorial account, based on 'parts' and 'relations'. One can view an object as being characterised by a set of constituent *parts*, and by the *relations* which establish how those parts are configured. Thus, design is a process in which designers identify constituent *parts* of the artefact they are trying to create, and assemble these under appropriate *relations* to produce a new whole.

The key to the parts-and-relations view is that it lifts the focus from visible design elements to more abstract design elements. What designers 'select' may not be a part (e.g., a visual element), but may instead be a relation (e.g., an essence, a configuration). So the parts and relations view accounts not just for direct translations, but also for more abstract interpretations of sources of inspiration. Thus, some designs may be novel because they put together *new* combinations of components in *established* ways (Figure 6, a). Others may be novel because *known* sets of components have been assembled in *new* relations (Figure 6, b).

Figure 6 Combining new elements to form new objects

The observed selection, adaptation and transformation strategies can be understood as means for finding and using interesting parts and relations from the source, in order to place them (and possibly re-configure them) into the new design. In general, the early design process involves selection of parts and relations, the recognition and understanding of emergent relations, and the setting of new relations and understanding of their consequences. So early design negotiates (both creating and comprehending) a developing context with both designed and emergent relations.

Further, this proposed combinatorial account helps us to explicate many interesting characteristics of the design process and its outcomes observed in phase 1.

Closing the loop on the design accounts

The decision sequence accounts derived in phase 1 – and specifically the aspects of the design process which they highlight – can be understood in terms of this parts-and-relations view of design.

- The simple design decisions on which each of the accounts is based correspond to identifying constituent *parts* of the artefact and assembling them under appropriate *relations*. The emphasis on simple decisions provides a mechanism for limiting focus.
- The sequence of decisions corresponds to the accumulation of parts-and-relations combinations. The sequence provides a developing design context, that is, the accumulated relations – and their developing inter-relations – provide a backdrop against which subsequent parts-and-relations decisions are made.
- Known solutions embody design abstractions which correspond to parts-and-relations combinations.
- The view of design through simple decisions in sequence which builds a design context is inherently incremental. The evaluation of decisions leads to iteration through the developing structure of decisions.

Complexity through combination

Given that the set of available components is large (as we can see that the number of components one might identify even in our two sources is large), then the possible combinations of those parts is huge. Complexity here is in terms of size of the combinatorial space – the number of possible parts and relations. And the complexity is amplified because the simple combinations can in turn be composed into other combinations.

In addition to the sheer scale of the space of possible solutions, there is the effect of interactions among elements and combinations. Each design decision (e.g., each new selection and relation of parts) contributes to a growing context for the design. Complexity arises here not just from numbers of possibilities but from interactions among design choices. The assembled parts may have emergent properties not possessed by their components. That is, more complexity is introduced because of new properties that arise from the interactions among elements. For example: unrelated parts in relation can start to look like something else (e.g., fried eggs and sausage on a plate looking like a face); parts in relation may assume a dominance in the balance of the overall design that the parts would not command individually; parts in repeated combination may suggest a rhythm or pattern in the overall design (e.g., a repeated letter ‘c’ – *ccccccccc* – suggesting a scalloped pattern or waves); and so on.

In other words, simple combination of simple elements leads to complexity.

Managing complexity by restricting focus

The parts-and-relations view not only provides an insight into how readily complexity can arise from a sequence of simple decisions, but also provides an insight into a mechanism for managing complexity by restricting focus. Complexity is sustained through the whole network of relations, but the designer can treat the division into parts as a way of ‘modularising’ the design space. As observed, designers normally work on one part of the design at a time, for example handling the central motif separately from the border.

An index of communication

Having a repertoire (a body of experience of design) allows a designer to use known solutions in new contexts. In order for the designer to re-use or refer to solutions, the repertoire must be accessible (which implies that it is organised in some way). Naming provides a means of access, allowing objects to be spoken about, referred to, and related to similar objects, both current and from prior experience (e.g., a 1940’s peplum jacket, a nautical central motif, last year’s autumn theme). We observed earlier that designers use labelled designs as an ‘index of communication’. Naming may adapt existing vocabulary to current activity and experience (e.g., use of metaphor), or may create new vocabulary (e.g., grouping instances or forming new associations). By naming we allow a parts-and-relation combination to be referred to as an entity. It also allows that entity to be related to other entities. Giving names is part of forming abstractions – the name can represent an abstraction over a group of related instances (i.e., a group of similar parts-and relations combinations, e.g., sawtooth borders). And of course, naming can form abstractions over abstractions, thus creating a conceptual hierarchy (e.g., repeated geometric borders). So, for example, a designer in our study might name parts of the carpet design: chevron, diamond, horse, bract. Names might be given to classes of parts, such as repeated geometrics, joined-together flowers, or complex diamonds. Names might be given to parts in context: repeated chevrons border, three-diamond central motif, Greek key border enclosing a complex motif. Hence naming provides a way of categorising and structuring a repertoire (i.e., organising it into a conceptual structure of design abstractions) and accessing the repertoire.

Design inspiration

This combinatorial parts and relations view provides an insight into design inspiration – designers relate what they ‘see’ in sources of inspiration to their whole repertoire of design knowledge. Hence, selection and adaptation from a given source may be direct – or it may incorporate this interaction with the repertoire to produce something indirect or unexpected. This provides a context for understanding the ‘creative leap’, about which Cross [17] suggests: that the “perceptual act underlying creative insight in design is more akin to ‘bridging’ than ‘leaping’ the chasm between problem and solution.”

Clichés and design signatures

The parts-and-relations viewpoint allows us to understand design signatures (individual, company, style, cultural, etc.) in terms of ‘palettes’ or ‘repertoires’ or ‘preferences’ of particular elements and combinations and configurations. For example, Edwardian buildings may be characterised crucially by key architectural elements and proportions.

Some designers produce designs which identify them like a signature. This may involve using the same kind of materials (such as stainless steel columns in architecture) or a particular range of values for a given design parameter (such as a particular palette of colours in clothing design). Or it may involve the emergent properties of the whole, as in the ‘sweeping’ awning coverings of the Richard Rogers’ buildings. The implication is not that a designer repeats designs, but that, in the terms developed here, certain elements and/or relational sub-structures may recur throughout the designer’s work.

The description given here allows a distinction to be made between clichés determined by the inclusion of given sets of elements, and clichés determined by the relational structure between elements. The advantage of using clichés (i.e., design schemas or templates) is that they provide well-known structures and sub-structures as entities (perhaps named entities) at their own hierarchical levels, but they do not necessarily pre-empt original combinations of the clichéd elements with other elements or sub-structures.

Provisionality

The parts-and-relations account accommodates not just bottom up design but also design working down from abstractions or higher levels of granularity. Higher-level relational structures may be decided (e.g., a jumper will have a motif and border structure) before the lower-level parts-and-relations are filled in. This supports both the exploration of different instantiations of a selected higher-level structure (and possible iteration during that exploration), and the accommodation of indeterminacies and variabilities during design.

This is supported by naming, which allows a design element (whether a structural element such as a border or sleeve, or a surface pattern) to be referred to without going into detail. Naming allows reference to be made to design abstractions such as style or categories of design elements without a particular instantiation having been decided (e.g., ‘a Fair Isle pattern’ when the particular pattern is yet to be decided; ‘a 1940’s peplum jacket’, when the cut and dimensions of the peplum have yet to be specified).

Hence it is not necessary that a design is fully instantiated at any particular time. The importance of ‘provisionality’ and the ability to retain indeterminacies during the design process has been stressed in other design contexts as well, e.g., typographic design [18], architecture [19], and software design [20].

4 Phase 3: Computational modelling

4.1 Methodology for phase 3

Based on the results of the first two phases, we proposed a simple computational model divided into four steps: selection of ‘interesting’ graphical objects; adaptation of those objects; placing of the resulting objects onto the garment shape; and evaluation of the resulting garment. All phases are regarded as iterative, whether singly or in combination. In human performance, these steps appear to be bundled up in continuous multiple cycles of selection, adaptation and transformation, placement and evaluation. Our designers were continually selecting, re-selecting, transforming, placing and moving, and evaluating their designs as they sketched and re-sketched ideas.

To assess the viability of this model, we programmed it in C++ and our strategy was pragmatic: to use the simplest interpretations and implementations feasible. We therefore implemented the first three steps: selection, adaptation and transformation, and placement. The earlier studies made clear that evaluation is crucial in design, however we made the strategic and pragmatic decision not to incorporate evaluation into the computational model. First, the model concentrated on the transformation-from-source and therefore on generation activities. Second, our earlier studies concentrated on the reported and observed design process and did not elicit evaluation heuristics. Third, our focus was on the viability of the model. Therefore, our assessment was based on whether the model could generate reasonable proportions of plausible, aesthetically pleasing designs according to human judges, not whether it generated *only* good designs. Indeed even our human professional designers produced unpleasing designs (by their own estimation).

We used the implementation of our model to produce designs for the same simple knitted shape, using the same sources of visual inspiration as in the constrained tasks. Our focus was on the viability of the model, i.e. whether it could possibly reproduce designs comparable to those we had observed in our studies.

4.1.1 Selection

Human perception is a complex activity which is the subject of other, sophisticated modelling efforts (e.g., [21, 22, 23]) and is outside the scope of our work. Therefore, the first step in implementing our model was to define a simple process analogous to human perception that could be automated. We employed a technique for identifying blocks of pixels which could be identified as 'one element' in the source. This consisted of four steps:

1. digitise the sources of inspiration;
2. identify high contrast pixels. The technique of thresholding was employed. 'Thresholding' identifies objects on the basis of whether or not the intensity of a pixel exceeds a given threshold value. This value can be calculated automatically [24];
3. identify horizontal runs of high contrast pixels;
4. identify contiguous horizontal runs which can be aggregated to form a polygon.

This process of translating a set of pixels into a polygon is illustrated in Figure 7 below.; the resulting polygons were taken as the 'interesting objects' to be placed on the garment shape.
The parameters for the size of horizontal runs and the number of contiguous runs could be varied by the user. The effect of this was to identify different elements from the source and therefore to create different images.

Figure 7 Translating a set of pixels into a polygon

4.1.2 Adaptation and Transformation

For each individual 'interesting object' extracted from the source, our implementation could apply two adaptations: literal; or modification through re-arrangement or combination. In addition, simplification through reducing the number of colours and losing detail was a by-product of the selection strategy adopted, and was therefore supported automatically.
The transformations that could be applied were: translation (moving to a different location), reflection (about a vertical axis), rotation (through 90 degrees), and scaling (half size or double size).

4.1.3 Placement

Placement strategies were not identified explicitly from phase two. However, designers' selection strategies included some placement mechanisms: central motif, overall pattern or border. Our implementation used placement strategies of: horizontal stripe; vertical stripe; all-over design, with objects placed randomly; all-over design, with objects placed on a randomly-sized grid; single motif, placed centrally; single motif, placed randomly; and border (around the bottom of the body and the end of the sleeves).

In our program, each 'interesting object' that had been selected for inclusion in the design was associated with a ‘placement’ in an object-placement pair, and these were then instantiated onto the garment shape. However, apart from the border and central motif placements, no account was taken of the exact location where objects would be placed on the shape. For example, when generating the random grid for an all-over design, no action was taken to make sure that the pattern row finished with a complete object at the neckline, or sleeve edge. In this sense, the placement strategy was unsophisticated.

The overall plan for a given knitwear design was specifiable by the user or determined randomly by the program, in terms of:

- the number of objects;
- the specific objects and their placements;
- a specific combination of object-placement pairs, (e.g., combining one object in a border with another in a central motif); and
- the colours to be used.

Our observations from phase two also indicated that placing objects onto a garment shape is context dependent. It is influenced by the overall plan for the garment, so that designers tend to place objects in classifiable positions. Object placement is also context-dependent because it is influenced by the prior placements of other elements. We modelled this behaviour in part with three heuristics:

- for certain kinds of objects ('open' shapes which partially enclosed a space, such as a 'C' shape), placement would be repeated with the object reversed;
- any open spaces would be filled;
- the 'all-over' placement excluded any other placements.

4.2 *Findings from phase 3: computational modelling*

Having tried a variety of values for the parameters determining which objects would be chosen, the parameters used were set at threshold 64 for the carpet and 32 for the wall hanging; for the majority of the design generation, we used 50 x 50 as the size of the object. The threshold figures varied because of the relative contrast in each image.

Although the system allowed the user to specify the overall plan for a garment by manipulating four constraints (number of objects, specific object-placement pairs, combinations of object-placement pairs, and colours), and we explored numerous variations of those constraints, our assessment concentrated on designs generated with minimal human intervention. We did this in order to test fully the viability of our model, since if the user were to choose the object-placement pairs, for example, then an element of human design is introduced into the process.

Hence, in the designs below, the program was entirely responsible for the design decisions. Leaving constraints unspecified meant that the full range of design heuristics built into the implementation were employed, including the heuristics for making decisions in the context of a developing design. The assessment focused on viability – on the ability of the program to produce reasonable numbers of designs comparable to those produced by the observed designers – and hence the trials focused on designs generated substantially by the implemented model. This paper concentrates on those examples (see Figures 8-11)

The software generated some designs that are comparable with designers' output, for example, Figure 8 a and b show comparable pairs of designs, one generated by a designer and one generated by the computational model. Figure 8b shows an example of comparable literal adaptation. The resolution of the images taken from the sources meant that when they were increased in size the pattern became fuzzy, but it is still possible to see that the central motif chosen is the owl.

a) an example of a random pattern
b) an example of a central motif with the owl as motif
Figure 8 Designs generated by designer and by computational model software.

As another example consider Figure 9. The designer's sketch shows a cable feature. The software's version produces a similar effect using an all-over pattern on a grid.

Figure 9 Designs generated by designer and by computational model software.

Not surprisingly the machine-generated designs are not able to produce designs deliberately using abstraction, but some of the randomly-generated designs create interesting juxtapositions and overlaps that might be the basis of further inspiration, and result in emerging properties. For example see Figure 10.

Figure 10 Abstract designs illustrating emergent properties, generated by designer and by model.

Other automatically-generated designs that have a 'designerly' quality are shown in Figure 11.

Figure 11 'Designerly' designs produced by the computational model software

On the order of 20% of the automatically-generated designs were deemed acceptably pleasing by human judges. There were evident comparisons to be drawn between automatically-generated acceptable designs and human-generated designs. None of the automatically-generated designs reached the design quality of the best human-generated designs, but our aim was to test the viability of the model, not to show that it could produce designer-quality designs.

4.3 *Discussion of phase 3*

The explicit computational process modelled in software has allowed a formal description of a creative design process. This model uses simple techniques for selection and adaptation, and simple contextual strategies. These techniques and strategies were based on those observed by our designers in Phase 2. Some of the designs produced by our model are chaotic and would not be chosen for further development by human designers (indeed, they would never be sketched in the first place). Our system has no evaluation component, and so is unable to avoid these designs.

We compared automatically-generated designs to those produced by professionals in phase 2, using both team members and independent third-parties. Although the automatically-generated designs are typically less sophisticated than those produced by professional designers, they nevertheless display some comparability – people recognise them as plausible and ‘pleasing’ designs. So, despite its simplicity the model is able to take advantage of ‘emergence’ and is capable of generating some ‘pleasing’ designs which display characteristics also displayed in human-generated designs, thus corroborating to some degree our proposal that a substantial part of complex design can be accounted for as part-relation combination.

4.4 Limitations and further work on the computational model

This computational model is a simple interpretation of the designer processes we identified through previous phases. As discussed above the model does not take into account various aspects of the design process we observed in our studies:

1. It does not include all the adaptation and transformation strategies observed;
2. The strategy for placing objects on the garment shape is not sophisticated;

3. The computational model does it include any evaluation

Future work on the model could include adding capabilities to address these three areas. A key aspect of future work on the computational model is to focus on evaluation, which we discuss below.

4.4.1 Evaluation

The evaluation problem may be thought of as combining two different aspects: first that of identifying suitable criteria for judgment of 'goodness' and second that of searching through the space of possible designs in order to identify designs that are good enough.

The technical constraints on performing a search through a large design space are relatively easy to formulate and will not be discussed here, but the aesthetic constraints are much more difficult to define, and much more controversial. Since we come at this from a computational perspective, our first task is to formulate properties of designs which can be recognised by the machine. These must relate to human criteria, but in the first instance may seem very ordinary compared to the discourse of a human designer. The designs we have generated suggest some criteria for evaluation, each of which could be 'computed' automatically. For example:

1. **Symmetry**
   Symmetry is an important organising principle in design. Devising an operational definition of symmetry for automatic recognition has significant pattern recognition problems. However, patterns laid out on a grid may have underlying symmetry which could be useful. Otherwise various *axes of symmetry* could be established, and one side of the axis be reflected to the other for matching. In the simplest case one could define a measure of symmetry based on numbers of matching pixels. Better would be to define symmetry in terms of matching objects made up from pixels. These measures could be further refined by consideration of colour.
2. **Regularity/Randomness**
   Some of the images we generated left large areas with no pattern. Certainly this is a striking visual feature, which can be recognised automatically
3. **Shape Repetition**
   Some of our designs used a single shape to create patterns while others used many abstracted shapes.
4. **Colour Combinations and Contrasts**
   Colour is obviously an import aspect of a design, and colours come and go from fashion as much as shapes and geometric arrangements. The numbers of different coloured pixels can be counted, and they can be refined with reference to objects. Contrasts can also be computed, with pixels of one colour close to pixels of another, or areas of one colour being close to areas of another.

From a technical viewpoint the search selection mechanism could be done on the fly, applied to populations of designs, or both. Evaluation of a single design on the fly has the lowest computational complexity. Evaluation of designs from populations may have higher computational complexity, for example if every design were compared with every other the number of comparisons would be of the order of the square of the number of designs. If the population contained in a small number of designs, say ten, then one hundred comparisons would probably be computationally feasible. If the population contained a million designs, the implied (1,000,00 x 1,000,000)/2 calculated could be too many to compute in the available time.

The following discussion considers a few of the many search techniques available to aid selection of the 'best' designs:

1. **Hill climbing and gradient descent**
   The idea in hill-climbing is that, from a given design, one examines other designs and if they are better discard the current design to retain the better design. This means that one is always getting better. If the other designs being evaluated come from the same part of the search space, one may end up with a local optimum which, nonetheless, is not very good from a global perspective. For example, the MIND research has shown that some designers become *fixated* so that all their designs have some common theme or property. This fixation limits the design space these designers will examine and they may miss much better options available to less fixated designers. However it may be that subspace to which they are fixated contained particularly good designs which are close to the global optimum. The problem with this kind of search is that you don't know whether you're in a good part of the search space or not. Of course the market may help in this, but not always, and not always predictably.
2. **Genetic Algorithms**
   This approach is based on an evolutionary analogy. In this case 'good' designs can 'breed' new designs. The approach involves representing the design as a sequence of symbols, for example *abcdef* where *a* may be a shape property, *b* a colour property, and so on. Then another design encoded, say, *vwxyz* could breed with *abcde* to produce, for example, the offspring *abxzw* and *vwcde*. This new population is then evaluated and the 'fittest' go through to breed a new generation of designs. *Mutation* is an important feature of this approach. For example, *abxyz* might arbitrarily be mutated to give *abmyx*, with the offspring having properties possessed by neither parent design. This corresponds to a 'new idea' of innovation. This approach is attractive because there is evidence that design does indeed follow an evolutionary path following innovations [25]. Designers following an evolutionary approach attempt to find selection criteria which will eventually match the selection criteria of the market where designs and the reputation of designers literally live or die.
3. **Simulated Annealing**
   The idea in simulated annealing is that you jump around the search space rather wildly at first, but the jumps become less wild as time goes on. This is done by setting a probability for accepting less good designs, and reducing the probability until the search becomes a hill climb. For example, a designer may try something completely new which gives a horrible result. But instead of rejecting it, the designer may make some modifications which in turn may also be horrible, or may result in something more aesthetically pleasing. This approach is relevant at the generation stage, when novelty is an important consideration.
4. **Neural networks**
   Although neural networks are not strictly speaking a search technique, they are included here because they may be very useful in implementing search and selections. In particular they can *learn* from examples. Neural networks are input-

> output devices, and they can be thought of as pattern-recognisers. To be used the design has to be represented by a sequence of numbers, perhaps associated with the descriptive features defined previously. This is the input to the network. The output could be a number representing a judgement such as ‘good’ or ‘bad’, but is more likely to be something like ‘good balance’, or ‘good shape’. Neural networks offer a bridge between the abstract computational model, and the expert knowledge and judgment of a human designer. Give a particular design, the computer can generate a numerical representation, and the human designers can give an assessment of the goodness/badness of the design on various dimensions.

More recently others have used computational methods to search aesthetic spaces. Kelly [26] has used genetic algorithms to search colour space for aesthetically pleasing colour combinations. Glaze [27] used a rule-based system to decide that designs were ‘bad’ or ‘not bad’. The subtlety of this is that violating a single rule can make some designs absolutely bad. Designs which don’t break any rules are ‘not bad’ with respect to those rules, but not necessarily good with respect to other criteria. Often the judgement of ‘good’ depends on interacting criteria which may be very hard to compute. Of course, expert designers break rules deliberately for effect or emphasis, producing better rather than worse designs.

5 Summary discussion

Our findings suggest that the source-to-design transformation process uses a repertoire of relatively few, simple mechanisms for selecting and adapting design elements from inspirational sources. Our simple cognitive accounts are based on a view of designs as elements in combination and configuration. Simple mechanisms may be employed in sequences or combinations. Complexity in the overall design arises from combination and configuration, so that simple design elements may stand in a complex network of relationships, from which new design properties may emerge. Hence, design expertise requires skill at least in:

- the selection of elements that satisfy the design constraints, and in
- the construction of appropriate relationships among elements.

Design expertise requires the management of the design solution space in accordance with external constraints (such as those imposed by market, medium, and manufacture) and design choices (which create a context of design decisions and may be treated as the self-imposition of constraints). We speculate that expertise also requires insight into when to strengthen or relax constraints. Under these accounts, the ‘magic’ of design resides in the evaluation heuristics that allow designers to constrain, search, and reformulate the solution space effectively.

In the design of most physical objects, the inspiration is visual, and the transformation of inspiration to design involves spatial reasoning. Design comprises the rapid alternation of the synthesis of designs by juxtaposing and transforming design elements, with analytical critical thinking about resultant relationships, and with the evaluation of the designs according to sets of constraints (e.g., [28, 29]). Producing designs involves combinations of designing sub-tasks and problem-solving sub-tasks (e.g., [30]) The interaction between design constraints, design processes (such as transformation operations), and evaluation (based on both aesthetic and technical criteria) is of crucial interest. Previous work has observed processes in which quickly-generated conceptual designs are filtered by making rapid evaluations based on aesthetic and technical criteria (in knitwear design [31]; in architectural design [32, 28]).

Drawing on our observations of professional knitwear designer behaviour, we have modelled processes involved in the use of inspirational sources in the design of knitwear motifs or surface patterns. This modelling, although simple, implements a variety of aspects of spatial reasoning and manipulation, including: selection of design elements from a source; abstraction and transformation of the selected elements for use in a new design; combination of selected or transformed elements into new elements; and context-sensitive placement of elements in an overall design.

The use of sources of inspiration can be understood as the identification of elements and relationships within the source, the selection for a design purpose, and the re-application of those elements and relationships in a new design context. The ‘disassembly’ of sources may sometimes lead to discovery of latent relational structure not deliberately designed in.

5.1 Limitations

Of course, the studies reported here have limitations, not least because of the chosen domain of study, knitwear. The very qualities that make knitwear a tractable domain for study also limit the conclusions we can draw from its study. However, the characteristics knitwear shares with other design domains (as enumerated in Section 1) make it reasonable to generalise with care from these studies, particularly with respect to the issues of uses of sources of inspiration, uses of visual elements, and spatial reasoning.

Similarly, various choices in the study designs might well have an impact on the design outcomes. The sources used, although chosen to be rich, representative, and different from each other, are a potential limitation. It is conceivable that different sources might yield different outcome. The use of the simple garment shape, too, may have simplified the behaviours. It is possible that a more complex shape might require more complex strategies.

We have proposed a simple model and demonstrated reasonably its ability to account for observed design behaviour. However, although plausible, it is not necessarily the true or the only account for that behaviour. Its importance lies in exposing the power of the parts-and-relations view, and the associated notion of complexity through combination of simple mechanisms to account for design complexity. The model – and the studies that underpin it – provide a foundation from which we propose some generalisations to be investigated through further studies.

5.2 Future work

The previous section suggests several ways in which the work could be developed within knitwear design, using different sources, different tasks, different garment shapes. Future work might investigate not just use of visual elements, but feasibility as a knitted garment and how it hangs on a human body. Clearly, it could also be developed in other design domains, where use of sources of inspiration and re-use of design might take different forms.

But for us the most important direction for further work is evaluation. The simple implementation of the computational model sidesteps the evaluation issue, in part by embodying some design knowledge (e.g., the definitions of the placements, use of a single, fixed shape). An immediate further step would be to weaken the design knowledge embodied in the implementation, to eliminate implicit and tacit knowledge that has crept into it, and to implement only what is explicitly part of the model. This would force us to expand the computational model to encompass parts of the process which were not yet implemented and to begin to address evaluation and in particular to articulate and formalise evaluation mechanisms.

5.3 Conclusion

The research aimed to analyse early stages in the design process — where ideas come from and how they are transformed — and hence to improve our understanding of spatial reasoning in design, the role of mental imagery, and the role of sketching.
In the introduction, we posed three questions which this research has addressed:

1. What is the nature of sources of inspiration, and how are they used?

We found that designers create and immerse themselves in inspiration-rich environments, including a huge variety of different types of sources. They use these sources extensively in conceptual design in a wide range of ways from literal adoption through various forms of selection and translation, to essence abstraction. They draw on both parts (elements of the source) and structures (relations between the elements).

2. Is there commonality of behaviour among designers in the early design process with respect to use of sources of inspiration?

We did find broad commonality in the use of sources of inspiration. The designers we observed all collect, use and share multiple sources of inspiration. They also draw on the repertoire of their own experiences and they discuss design in terms of common repertoires of known solutions. The design process is typically iterative and incremental. Designers often focus on one part at a time and make simple decisions. They maintain an awareness of context and how each decision changes the design context.

Designers use sketching extensively in design. The nature of the sketching activity suggests that it is both expressive and reflective.

3. Are there discernable design ‘sub-processes’ in common use?

Through our sequence of studies we have identified and analysed some of the constituent behaviours in using sources of inspiration in knitwear design: selecting, adapting, and transforming. We have articulated some of these formally through computational modelling.

Through this research, we have offered some simple general accounts of observed design behaviour and have shown how a simple parts-and-relations account can explicate aspects of both subtlety and complexity in design.

6 Acknowledgements:

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Figure captions

Figure 1. A simple process model of design.

Figure 2. A simple garment shape.

Figure 3. The Persian carpet used as a source of inspiration.

Figure 4. The William Morris wall hanging used as a source of inspiration

Figure 5. Designers’ designs: examples of the kinds of adaptation executed by designers.

Figure 6. Combining new elements to form new objects

Figure 7. Translating a set of pixels into a polygon.

Figure 8. Designs generated by designer and by computational model software.

Figure 9. Designs generated by designer and by computational model software.

Figure 10. Abstract designs illustrating emergent properties, generated by designer and by model.

Figure 11. 'Designerly' designs produced by the computational model software.

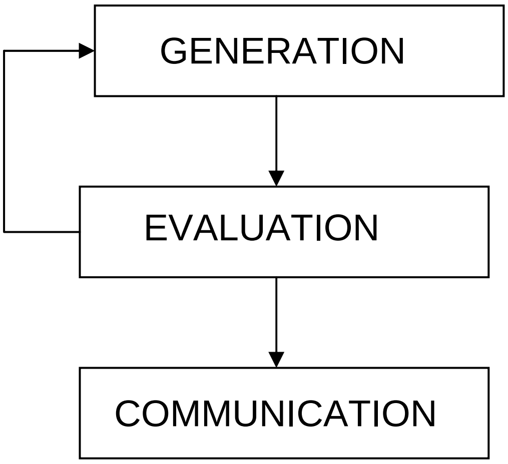


Figure 1 A simple process model of design

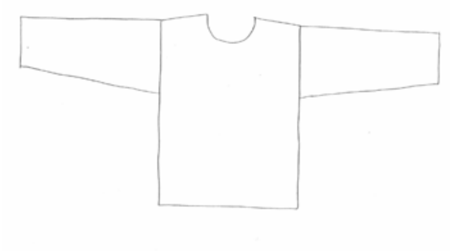
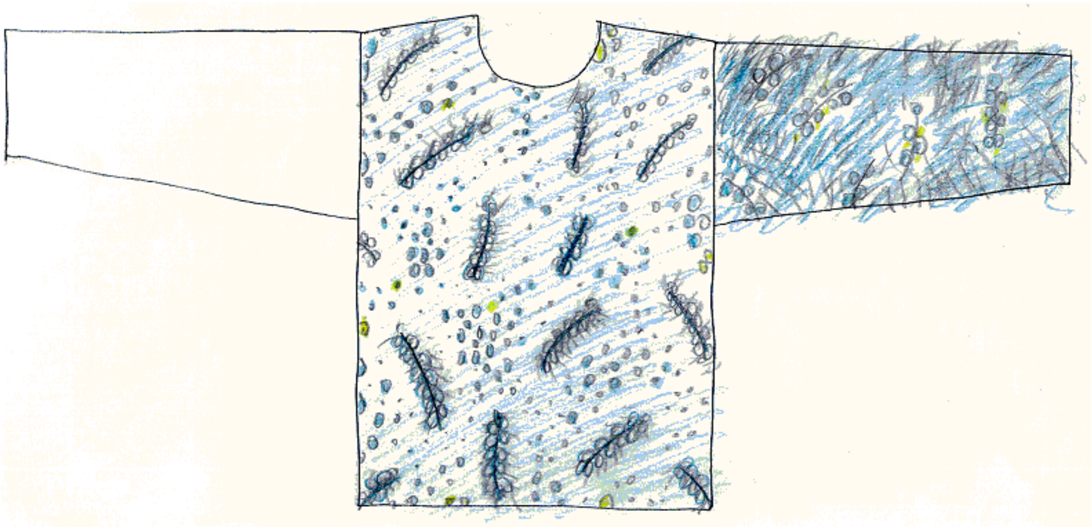


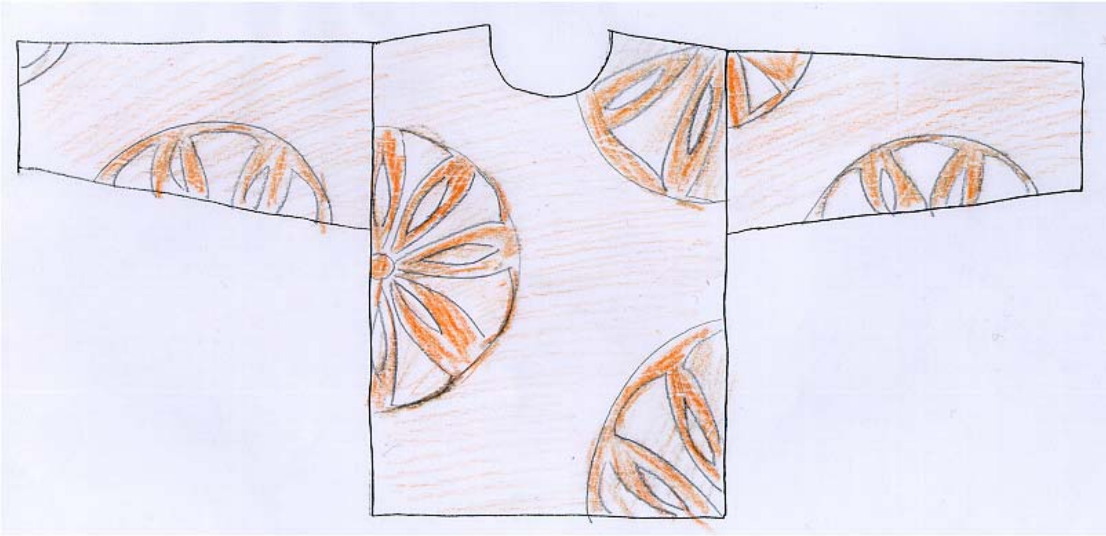
Figure 2 A simple garment shape

Figure 3

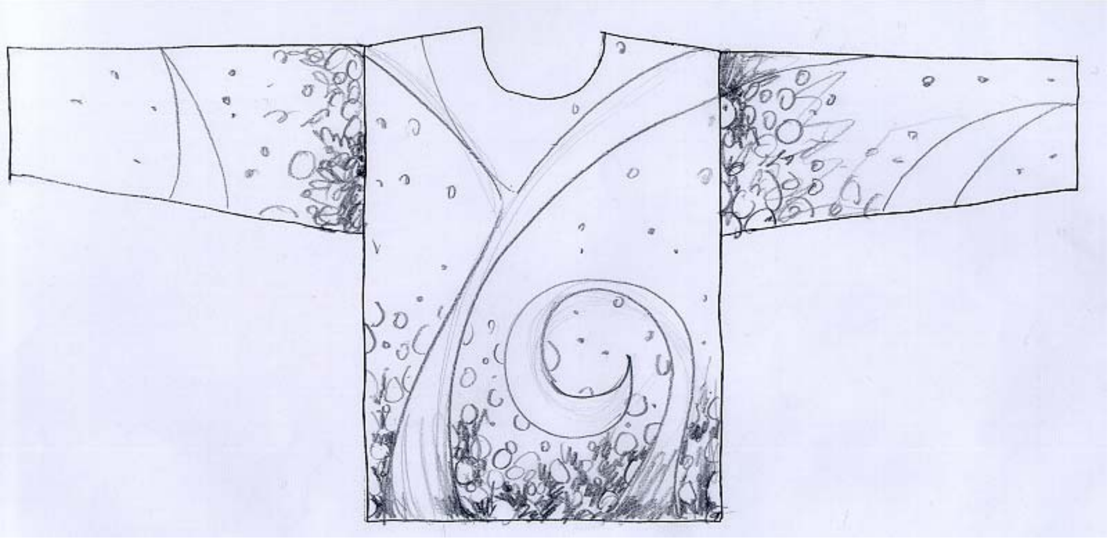
Figure 2. William Morris tapestry design used in the empirical studies.



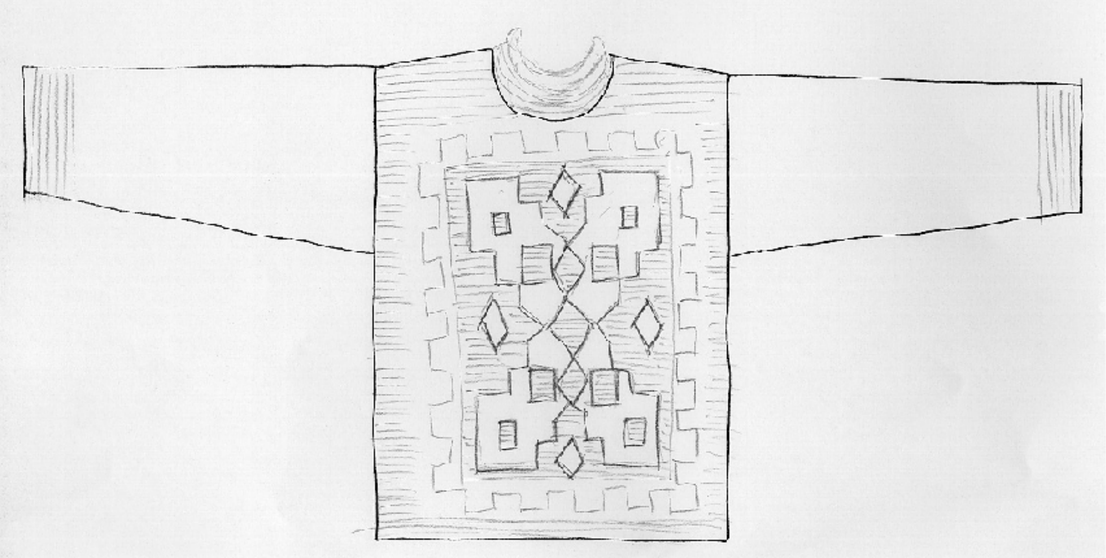
(a) An example of 'deviation' from wallhanging



(b) An example of 'association' from wallhanging

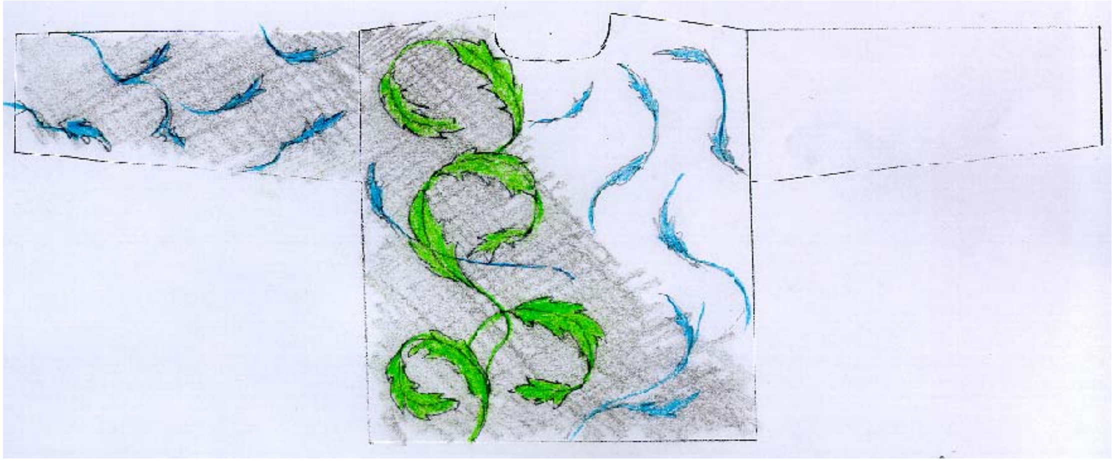


(c) An example of 'abstraction' from wallhanging



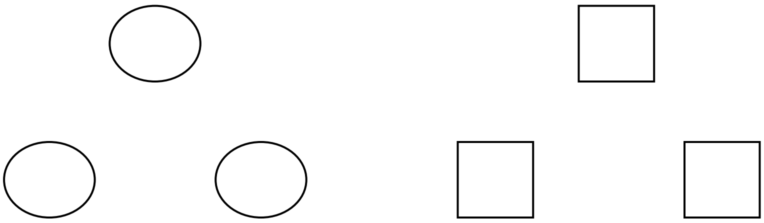
(d) An example of 'modification' from carpet.

(e) An example of 'simplification' from wallhanging



(f) An example of 'literal' from wallhanging

Figure 5 Designers' designs: examples of the kinds of adaptation executed by designers.



(a) different objects combined in the same relationship

(b) the same objects combined in a different relationship

Figure 6 Combining new elements to form new objects

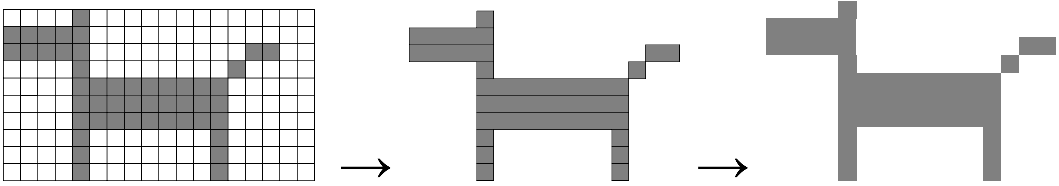
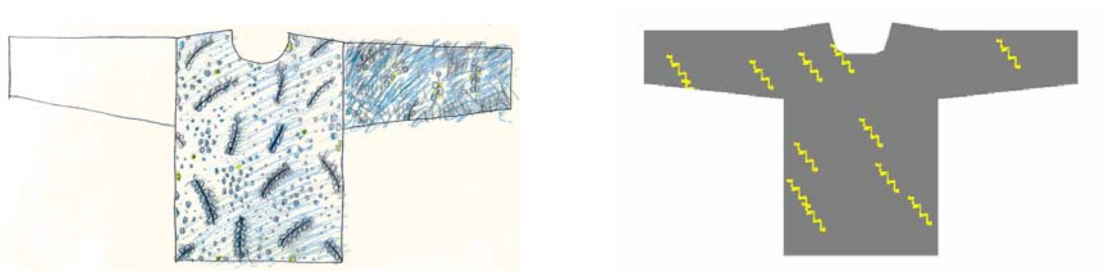
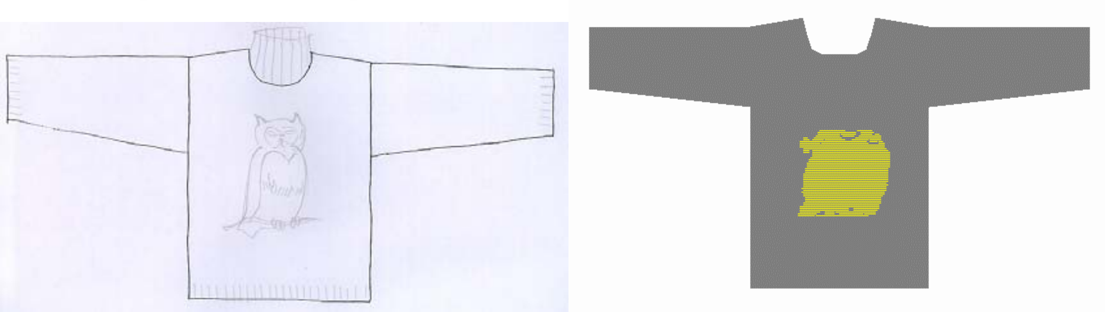


Figure 7 Translating a set of pixels into a polygon



a) an example of a random pattern



b) an example of a central motif with the owl as motif

Figure 8 Designs generated by designer and by computational model software.

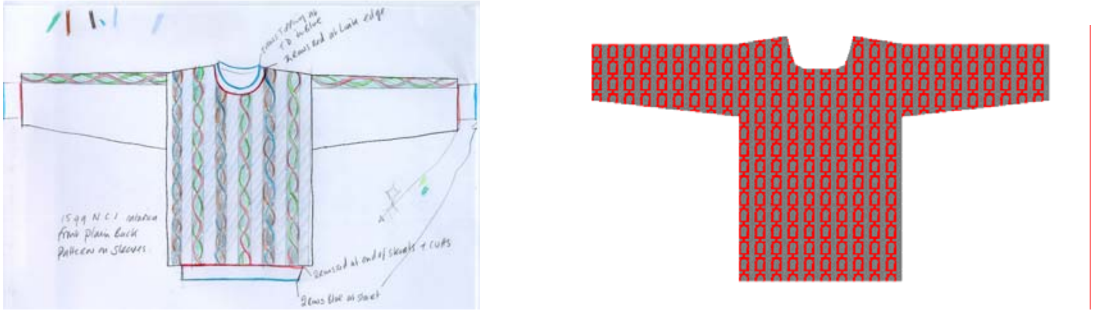


Figure 9 Designs generated by designer and by computational model software.

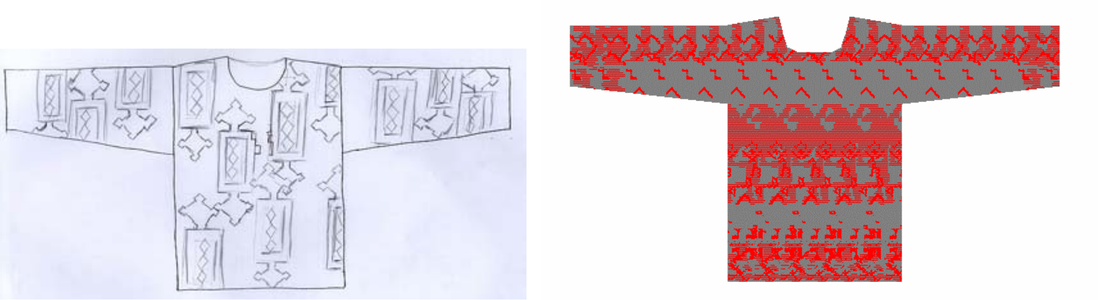


Figure 10 Abstract designs illustrating emergent properties, generated by designer and by model.

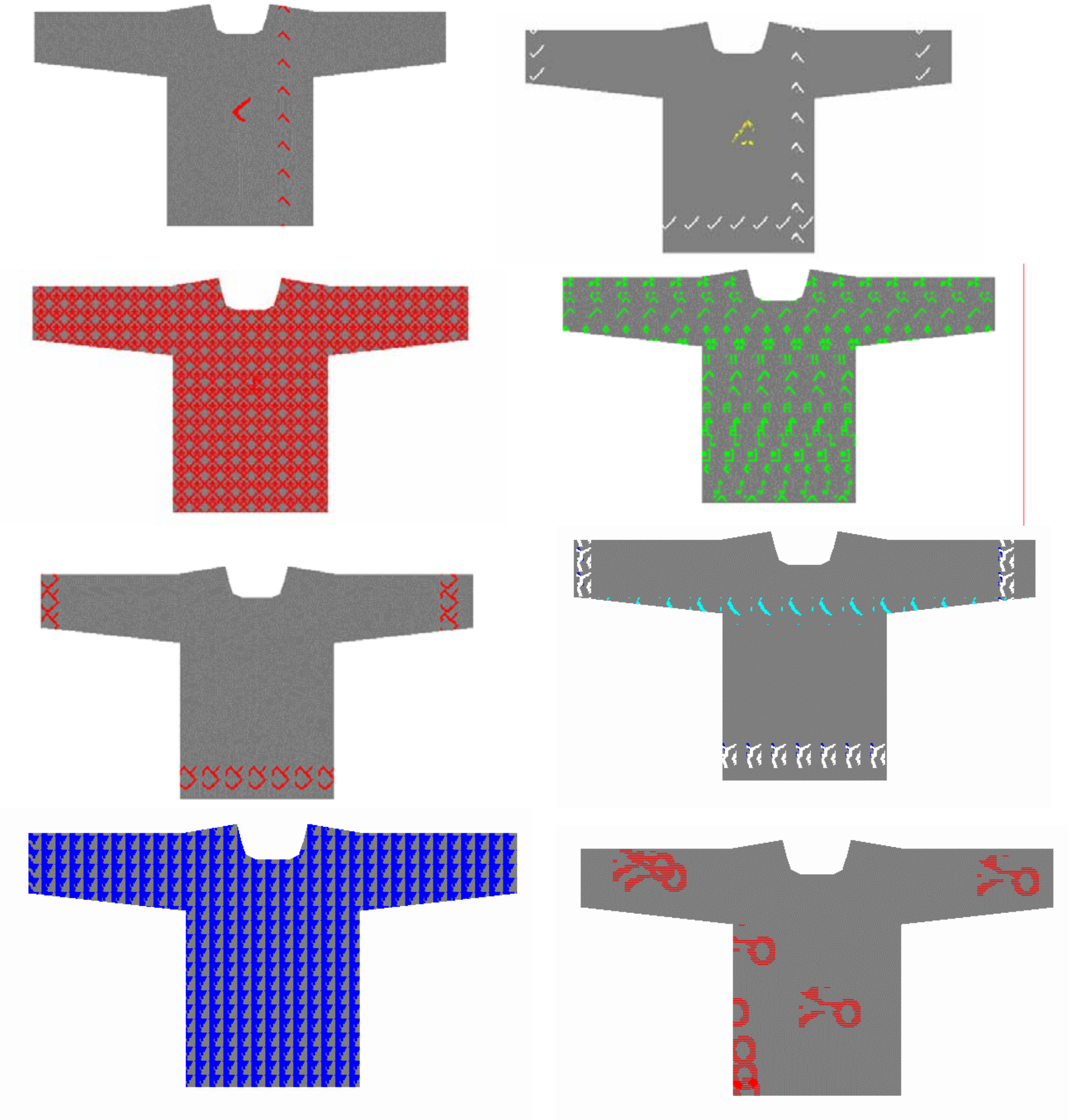


Figure 11 'Designerly' designs produced by the computational model software