Supporting Design Exploration

by

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Abstract

The aim of this research was to investigate strategies for the support of design exploration, in particular, how computer based technology could contribute to this activity during the early phase of design. The research comprised of the design and development of three software prototypes, the later versions of which enabled discussions with design professionals concerning the underpinning approach of the work. Three case studies of design practice were undertaken. These focused on the interdependencies between freehand drawing, physical modelling and CAD. Based on the research it was concluded that computer based support for exploration during the early phase of design was viable and that the generation of alternative solutions played a key role in the process. Furthermore, the approach offered by shape grammars provided a generative mechanism that was both grounded in the discipline of design and amenable to representation in a computer based system. Finally, it was concluded that the introduction of a 'controlled irregularity' into the resulting design alternatives increased their likelihood of encouraging design exploration.

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1 An Introduction to the Research

1.1 Aim of the Research

The aim of this research is to investigate strategies for the support of design exploration. In particular how computer based technology could contribute to this activity during the early phase of design. Design exploration is viewed as an activity that is manifest in the production, manipulation and communication with, and through, alternative solutions and contributing to an enhanced understanding of a design problem. The research has drawn from work in Computing, Design and Psychology and has utilised requirements generation techniques informed by the Social Sciences.

1.2 Introduction

Design is solution focused (Lawson, 1994) and it is through the exploration of alternative solutions that the nature of the problem is revealed. Indeed for some designers the rapid iteration of alternatives is particularly important during the early phase of design process as decisions made at this point can have a profound impact on the eventual design solution. The early phase of design can be characterised as a period of intensive creative activity, where a designer is generating multiple alternatives either based around a theme or each reflecting the parallel lines of thought of the designer. In general, such alternative solutions are articulated in the form of hand drawn sketches. How computer based technologies might usefully contribute to such a creative, dynamic and highly personal area of a designer's work is a question that permeates the research reported in this thesis.

A further component of the research is co-operative behaviour within human groups. In particular, the potential benefits associated with the adoption of a co-operative strategy during problem solving and, specifically, the maintenance of an environment where solutions can be refined through logical argument and the resolution of different perspectives. Essential to this view is the ability of any participant to generate and communicate alternative solutions, as it is these that spark the iterative process implicit in co-operation (Broadbent, 1973).

The research will draw parallels between a co-operative approach to problem solving and the activities which characterise the early phase of design; in particular, the role of alternative solutions and latterly the idea of co-operation with the 'self' through the medium of tools. It is important for the reader to note that over the duration of the research the nature of the relationship between co-operation and design has altered. At the outset the aim was to investigate the utility of a Human Computer Interaction (HCI) paradigm based on co-operation. To this end design was selected purely as a suitable task domain in which to explore the potential for co-operation between a user and a computer. At the completion of the first prototype P0 a shift in emphasis occurred and the study of design began to assume an increased priority within the research. Rather than trying to embody co-operation within technology, co-operation became influential in framing the author's interpretation of design and the consequent prototypes P1 and P2. In short, the activity of design was interpreted as a co-operative process rather than a process that exemplified co-operation.

The nomenclature P0, P1 and P2 associated with the prototypes developed during the course of the research has been selected in order to emphasise the distinctiveness of each at both the strategic and temporal levels. P0 reflects the initial HCI orientation of the research, while P1 and P2 exemplify the design focus of the later work.

1.3 Summary of the Research Conducted

An initial software prototype P0 was developed to study how alternative solutions could be generated and interwoven into a task based interaction. The activity of design was selected, specifically the task of space planning, as its open ended nature was considered suitable to a co-operative approach. A system was developed based around the idea of locating items of furniture within an office floor plan. The task offered the benefits of a limited object set but a potentially infinite number of configurations. Furthermore, the concept of goals could be introduced through the use of relational rules between objects. For example, telephones must always be located on desks. The prototype sought to generate alternative floor plans based on the designer's current solution and the priority of the rule set, which could be configured by the designer. An informal evaluation of the prototype, undertaken by final year design students at Loughborough University, produced favourable feedback concerning the nature of the interaction. In particular, the designers liked the explicit coupling of rules to the production of alternative solutions. However the prototype was criticised as being overly simplistic in terms of the design alternatives that it produced. This was due to the poverty of the prototype's underlying rule base. This perception was compounded by the highly specific nature of the task that the prototype sought to support, which in turn, lead to a raising of the designers' expectations as to the level of sophistication of the resulting alternative solutions.

At this stage in the research it became clear that if the task domain of design were to be used to articulate the concepts thought to underpin co-operation then research into the nature of the design process would be required. This realisation marked the beginning of an important shift of emphasis within the subsequent research.

The research emphasis on design was begun in earnest by undertaking three case studies of undergraduate interior architecture projects. The case studies were interview based and conducted over a 16-week period. The studies focused on the designer's usage of tools as this was considered to be indicative of the way that the designer's conceived of the task. Furthermore, as the aim of the research was now the design of computer based tools to support design, it was important that such an endeavour complemented existing design tools rather than seeking to replace them. The studies focused on the interdependencies between freehand drawing, physical modelling and Computer Aided Design (CAD). The studies revealed that both the degree of visualisation offered by each tool and their level of engagement with the designer were critical during the conceptual phase of the design process. This was particularly important during the generation and selection of alternative solutions. A position that developed during this study was that it is both possible and desirable for an individual to co-operate with the 'self' through the medium of tools. Indeed, that certain practitioners use design tools to initiate a dialogue with the problem at hand in a manner that is reminiscent of co-operative behaviour.

Based on the case studies, a number of scenarios of future systems were generated and presented to members of the professional interior design community. The resulting feedback provided the basis for an implementation of a second prototype system P1. The implementation utilised the technique of shape grammars (Stiny, 1975) as a design based technique for the production and manipulation of alternative solutions. As a result of their design heritage, shape grammars provided legitimacy to the representation of design, not previously attained by prototype P0. Furthermore, they offered a possible solution to the simplistic nature of the machine generated alternative design solutions exhibited by the earlier prototype. Shape grammars seek to formally represent the rules and objects associated with a particular design style. In the context of this research the approach offered a number of advantages. Firstly, a method for formally representing existing design styles; and secondly, the provision of a generative capability; and finally an opportunity to apply the reasoning capabilities of knowledge based systems within the context of design.

The prototype system utilised a basic shape grammar as defined by Knight (1999). The grammar comprised of rules that describe the spatial relationships between a square and a rectangle; the rules were additive and recursive. The initial version of the prototype P1, which was later evaluated by professional practitioners in the field of interior architecture, incorporated the concept of 'change' rules in the form of spatial labels. Change rules allow the designer to manipulate the grammar and thereby generate a range of alternative shape configurations. A second version of the prototype P2 extended this approach to the provision of a 'meta grammar' through the addition of a new class of change rule called 'loose-fit'. These rules introduced a level of uncertainty into the resulting shape configurations, the purpose of which was to encourage the designer to explore the solution potential of the grammar. The prototype P2 was used as a vehicle to discuss the applicability of the approach to the practice of design with the interior architects involved in the earlier envisionment process.

The research contributed to the body of knowledge in two ways. Firstly, by the finding that computer based support of the early phase of design can be enabled by the generation of alternative solutions. The act of production, coupled with the solutions themselves, act as a catalyst for an exploratory dialogue with the designer's self. Secondly, through the development of a new class of change rule, associated with shape grammars, called loose-fit. These rules allowed designers to introduce a degree of controlled irregularity into the shape configurations generated by the grammar, thereby increasing the likelihood of them inspiring design creativity.

A number of areas for further research have arisen from this work. They are based on either comments from the design practitioners or insights gained by the author during the course of conducting the research. In the short term, the prototype P2 could be extended to incorporate a colour grammar. In this case an overlap area of given shape combination might be coloured in ways specified by a rule set. Similarly, the generation of shape configurations could be suspended by the designer, an area selected, and a different rule set applied to the ongoing design. This approach could have the potential to extract new rules from the resulting shape configurations. This raises an interesting reflexive quality whereby rules can generate designs, but also that a design could be the source of new rules. The sense of engagement observed during the case studies of design tool usage suggested a longer-term topic of research. This centres on the haptic qualities of physical models that enable designers to manipulate, through touch, a 3D representation of a building space. The sense of engagement provided by such models was viewed by the designers as something qualitatively different to that provided by drawings, whether these were produced by hand or by CAD. The characterisation of the designer as 'thinking with their hands' while creating and manipulating physical models supports the findings of Candy & Edmonds (1996) and Roy (1993). The questions of how technology might provide designers with such essential attributes and, indeed, how might such requirements inform the design of the next generation of technologies are issues that the author intends to address in the forthcoming years.

1.4 Overview of Research Outcomes

The research explored the position that it is both possible and desirable for an individual to co-operate with the self during problem solving. This was achieved by using tools as a means of initiating a dialogue with the problem at hand. Central to this process was the ability of such tools to enable the generation and communication of alternative solutions. Studies of designers and interviews with practitioners has led to the approach being exercised in the domain of interior architecture, specifically space planning, through the use of shape grammars. These grammars offer a designer the ability to explore their shape generation potential through the use of change rules. The research extended this approach by the development of a new type of change rule, the loose-fit rule, which introduced a level of uncertainty into the resulting shape configurations.

The main conclusions from the research were as follows:

- that computer based tools have the potential to support the early phase of design through the production of alternative solutions and the ensuing exploratory dialogue that accompanies this process;
- the introduction of a degree of irregularity into these alternatives offers the possibility to expand design strategies and hence, the potential for creative solutions.

1.5 Guidelines for the Reader

The research reported in this thesis has drawn from work in Computing, Design and Psychology. This eclectic mixture is perhaps due to the ten-year period over which the research was conducted. Over this time, what was essentially research grounded in psychology and HCI with the aim of investigating the utility of an interaction paradigm based on co-operation, has transformed into the study of design exploration.

At the outset, design was literally used as a vehicle by which to articulate the author's nascent ideas concerning a co-operative interface. The realisation that one needed to 'know' about the domain that one was using marked the point where a change in emphasis began within the research.

In retrospect, such a shift is not surprising and indeed it would be worrying if one's ideas had not changed over such a time period. The influence of co-operation is a case in point. At the outset of the research it was the primary motivator, reaching a peak with the development of the first prototype P0. From that point on, a subtle shift of emphasis took place as the study of the design process became increasingly central and co-operation provided the context for the subsequent approach to the study of the design process. In particular through the role of alternative solutions and, latterly, through the idea of co-operation with the 'self' via the use of tools.

The author will argue that the strength of this research is as a result of the changing emphasis of the approach. Indeed, the prototypes P1 and P2 would not have assumed their final form without the underpinning provided by the earlier study of co-operation.

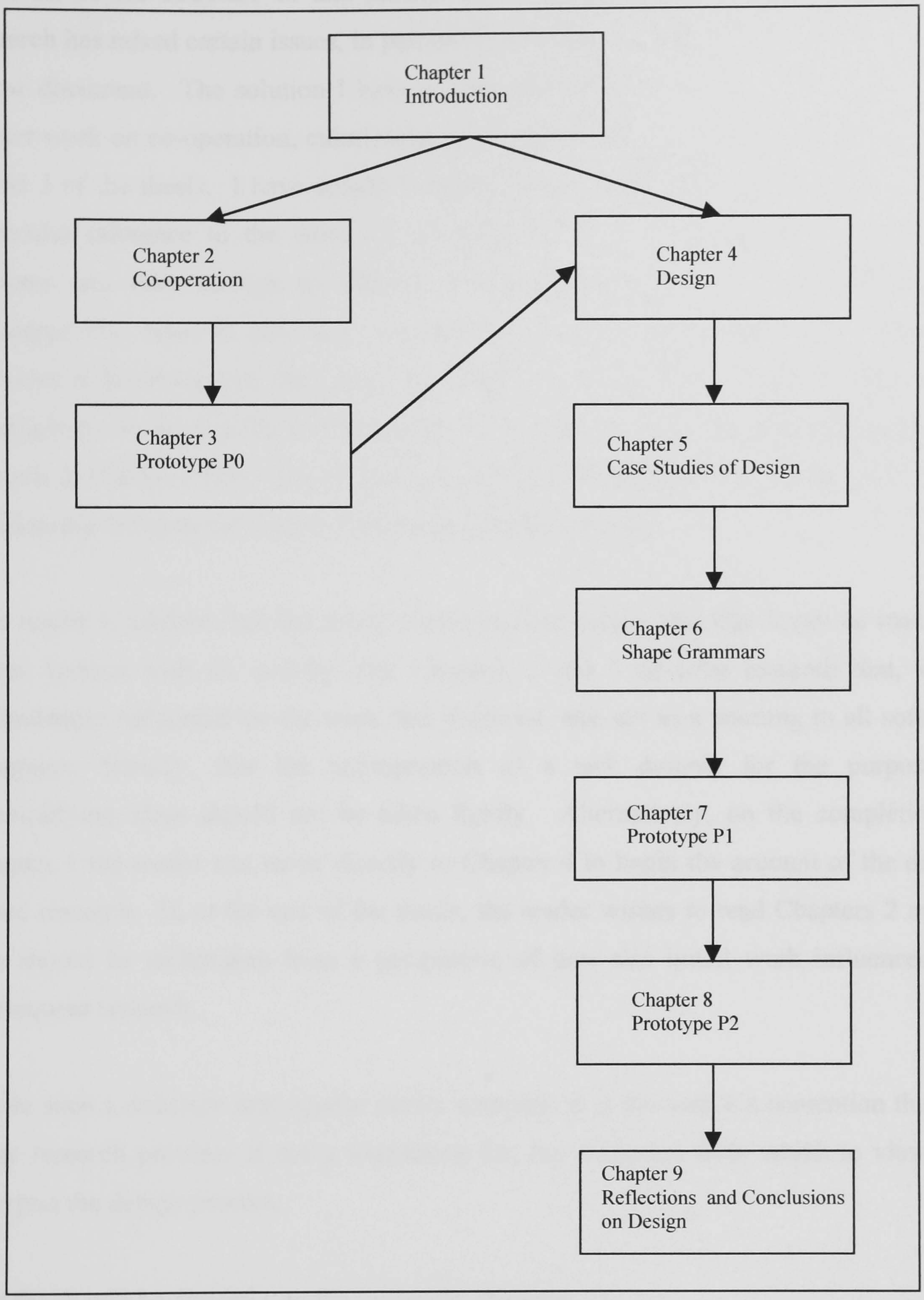


Figure 1.1 Visualisation of Thesis Structure – arrows indicate suggested reading route

In terms of the structure of this thesis, the changing emphasis and timescale of the research has raised certain issues, in particular, how best to reflect such interrelations in a linear document. The solution I have chosen is illustrated in Fig 1.1. Essentially the earlier work on co-operation, culminating in prototype P0, has been grouped in Chapters 2 and 3 of the thesis. I have sought to update the research reported in Chapter 2, with particular reference to the work on computer based critic systems and agent based systems and their attempt to address similar shortcomings to those discovered in prototype P0. Namely, how best to update the system's knowledge bases. Chapter 3 provides a description of that initial prototype and, again, I have used the benefits of hindsight to be more reflective about this work than when it was originally published (Smyth & Clarke, 1990). It was at the completion of prototype P0 that the shift in the relationship between co-operation and design began to occur.

The reader is advised that the thesis is structured in such a way that it can be read in a linear fashion with the proviso that Chapters 2 and 3 describe research that, while undoubtedly influential on the work that followed, also act as a warning to all software designers. Namely, that the appropriation of a task domain for the purpose of exemplifying ideas should not be taken lightly. Alternatively, on the completion of Chapter 1 the reader can move directly to Chapter 4 to begin the account of the design based research. If, at the end of the thesis, the reader wishes to read Chapters 2 and 3, this should be undertaken from a perspective of how this initial work influenced the subsequent research.

While such a structure may appear overly complex, it is the author's contention that the early research provides if not a foundation for, but a context from which to view and interpret the design process.

The thesis will be divided into the following chapters:

- A review of co-operative behaviour within human groups, including some implications for systems design;

- A description of an initial prototype system P0 with the aim of generating alternative design solutions;
- An introduction to design and in particular its support by computer based tools;
- Three case studies of tool usage among interior architecture students;
- An introduction to the approach of shape grammars as a technique to enable the articulation of design styles;
- A second prototype P1, which utilised the concept of shape grammars as a means of generating alternative solutions through interaction with change rules;
- Prototype P2 informed by a series of interviews with design practitioners leading to the inclusion of loose-fit rules with the purpose of introducing a level of uncertainty into the resulting shape configurations;
- Finally, a series of reflections and conclusions concerning the research reported in the thesis, together with a discussion of some areas for further work.

2 Co-operation – A Strategy for Interaction

2.1 Overview

This chapter will introduce the following:

- a review of the psychological literature relating to human co-operation;
- a discussion of the relationship between tasks and co-operation;
- a series of nascent guidelines for computer based technologies which aim to support co-operation;
- a summary of some pertinent human-computer collaboration systems.

2.2 Introduction

Co-operative behaviour has the potential to empower groups and the individuals of which they comprise. This raises the question of whether such empowerment can be harnessed to inform the design of interactive systems. Furthermore, might the subsequent characterisation of a computer as a co-operative partner result in the production of a more beneficial interaction style? As an initial step towards addressing this question, a review of co-operative behaviour is presented in Chapter 2.

The rationale of the work reported here is to enable the identification of the mechanisms that create and maintain co-operative behaviour among human groups. The research will reflect a strong psychological tradition and will report work from the fields of behavioural, organisational and social psychology. This distinction can be characterised as the study of co-operation at the level of the individual or the group. For example, the identification of personality characteristics that are indicative of an individual's likelihood to co-operate. While from the perspective of the group, co-operative behaviour can be studied in terms of the situational factors which impact on its occurrence, for example the accurate communication of shared goals within the group.

Where appropriate, links to technological systems are identified and the chapter concludes with a review of critic based systems. These systems are considered to be the closest to the spirit of co-operation and thus serve to orientate the reader towards the introduction of prototype P0 in Chapter 3. It is interesting to note that the majority of both the critic based and, to a lesser extent, the agent based systems are synonymous with the period between the late 1980s and the early 1990s. Not unsurprisingly that time coincides with the development of prototype P0. With the benefit of hindsight, the particular problems of how to update knowledge, as experienced by all three approaches, will be discussed, together with the various strategies adopted by each.

2.3 Introduction to Co-operation

Co-operation is an abstract concept in so far as there is no universal image associated with the idea (Argyle, 1991). In general, abstract concepts acquire their meaning through associations and relationships with concrete objects. No such universal image exists for co-operation. Undeniably, co-operation exists; we witness it and experience it all the time. The problem of characterisation lies in the fact that in one circumstance a particular behaviour may be deemed co-operative, whereas in another context the same behaviour may be seen as entirely inappropriate. For example, the repetition of the same advice irrespective of its applicability. Co-operative behaviour appears to be tightly bound to the context in which it occurs and to the task being undertaken. How then is co-operation recognised if it can take a variety of forms? Perhaps an analogy may clarify the situation. In his book The Image and the Eye, Gombrich (Gombrich, 1982) suggested that our interpretation of visual images depends on prior knowledge of possibilities. Also images are subject to interference, or noise, and therefore need the device of redundancy. Drawing on the analogy, co-operation can be thought of as a 'behavioural image' and as such may also require similar prior knowledge and redundancy. Like visual images, co-operative behaviour may rely more on ease of distinction from other behaviours than from fidelity of reproduction. For example, an individual's offer of help can be interpreted at face value as being non-competitive and the appropriate response made. While ulterior motives may become apparent at a later date, what is important is not having to wait until co-operative behaviour is recognised before a suitable response is offered. The question still remains as to what are the defining features associated with co-operative behaviour.

Dictionary definitions of co-operation provide more clarity as to the nature of this concept. For example, The Oxford English 2nd edition defines co-operation as 'working together, acting in conjunction (with another person or thing, to an end or purpose, or in a task)'. Webster's 3rd New International dictionary provides three definitions under the heading of co-operation. Firstly, 'to act or work with another or others to a common end, operate jointly'. Secondly, 'to act together: produce an effect jointly'. Finally, 'to associate with another, or others for mutual, often economic, benefit'. Based on these definitions, co-operation requires two or more parties working together towards a joint purpose.

From the perspective of social psychology, Morton Deutsch (1973) has suggested that the basic requirement for a co-operative situation is that an individual or group 'behaves in such a way as to increase his chances of goal attainment, he increases the chances that others .... will also attain their goals'. This description of co-operation differs from the earlier dictionary definitions as instead of attempting to define co-operation *per se*, Deutsch highlights behavioural conditions that contribute to the creation of a co-operative situation. Essentially co-operation is the condition in which the gains of one party are also the gains of the other.

2.4 Analysis of Co-operative Behaviour - Psychological versus Situational

Attempts to describe co-operation can be characterised by two approaches, the psychological and the situational approach. The psychological approach focuses on the individual characteristics of the participants, for example, personality characteristics as well as individual perceptions of the task, self and other participants. The situational approach focuses on the variables that define the setting of the group encounter, including task characteristics, number of participants, stage in the task and modes of interaction. Results from a series of experiments conducted by Marwell and Schmitt (Marwell and

Schmitt 1975) have indicated that psychological or subjective variables, as they refer to them, have not been strongly predictive of co-operative behaviour. Examples of such variables include motivation, self interest, trust and empathy toward others in the group. The problem lies in measurement, in that subjective variables require some kind of observable behaviour as an index, and to date there exists no inventory of such variables with established validity and reliability to predict co-operative behaviour. By contrast, they reported stronger effects for a variety of situational variables, either alone or in interaction with other situational variables or psychological variables. In particular two situational factors have been identified as being critical to the evolution and maintenance of co-operative behaviour; these are inequity and interpersonal risk.

Inequity concerns the basic relationship between behaviour and rewards (Axelrod, 1997, 1984). With single subjects inequity varies along two axes, the magnitude of the reward and the schedule of delivery of that reward. In the situation where more than one person is rewarded the comparative magnitude of the reward was a factor in how individuals assess the relative benefits of participation within the group. In the course of a co-operative relationship it can be assumed that participants will compare rewards and will use that as a standard in determining their overall satisfaction with the relationship. Dissatisfaction, based on a perceived inequity of rewards among group members, could lead to the following outcomes; a reduction of effort within the group so as to match perceived reward, attempts to alter the reward distribution, withdrawal from the group to a more unprofitable individual task and attempting to entice others to withdraw. In terms of rewards the removal of inequity from non-co-operative pairs generally leads to the resumption of co-operation and the provision of a mechanism for reward transfer increases the likelihood of co-operation.

The second variable, that of interpersonal risk, highlights the situation where an individual who enters a group relationship substantially reduces the extent of personal control during the solution development. The acceptance of dependency incurs the element of risk. On an individual level, the impact of risk relates to the problem of trust among group members and is likely to result in an initial reduction in co-operative behaviour prior to the development of a mutual trust among participants (Sherif and Sherif, 1969). In terms of group working the effects of interpersonal risk can be summarised as follows. Firstly, the introduction of interpersonal risk to a co-operative relationship has the effect of reducing the overall effectiveness of the group. Secondly, the removal of risk generally leads to a resumption of co-operation. Finally, the larger the risk, the greater the impact this has on the overall behaviour of the group. In general, many of the effects of interpersonal risk within groups can be reduced by the provision of channels of communication which, coupled with certain types of past relations where trust among the participants is high, can increase the likelihood of sustained co-operation.

A further situational factor that has an effect on group behaviour is the degree of anonymity between the members of the group. It has been suggested that anonymity can lead to perceptual changes resulting in a lowered threshold of normally restrained behaviour. Zimbardo (1970) referred to such lowering of behavioural thresholds as 'de-individualisation'. Indeed, later studies (Greenberg, 1979) have revealed that only some form of social contact, either through communication or past relations, produced any effects that differed markedly from the anonymous condition. The devolution of personal responsibility associated with group membership can result in an increase in risk taking, referred to as 'The Risky Shift Phenomena' (Stoner 1961). Although later studies have indicated that the tendency to 'shift to risk' should more properly be called a 'shift to extremity' as group decision making appears to polarise toward an extreme interpretation of the position initially favoured by the average of the individual choices (Brown 1993).

When set in the context of a society where technology enables an increasing number of relationships to be initiated and sustained in relatively impersonal ways, the propensity towards extreme behaviour in such situations should not be ignored. Technology has provided an array of electronic equipment by which relationships can be conducted. For example, the extensive use of electronic mail and research into Computer Supported Co-operative Working (CSCW), where computers are used to mediate the communication between geographically separate individuals or groups and the global communication offered by the World Wide Web (WWW). If the aim of CSCW research is that implied by the name, that is, to support co-operative working, then the results reported by Zimbardo and others must raise certain questions. Whether, for instance, social relations mediated by such technologies will ever be totally conducive to co-operative working, given the propensity of anonymity to encourage such extremes of behaviour among individuals.

2.5 Factors which Induce and Maintain Co-operative Behaviour

The context dependent nature of co-operative behaviour has mediated against the production of a universal description. Consequently, a number of studies have attempted to characterise the phenomenon in terms of situational factors that initially induce and consequently maintain co-operative behaviour. From this perspective co-operation can be viewed as a set of relations among behaviours and their consequences in a given context.

As part of an empirical study of dyads by Marwell and Schmitt (1975) five specific elements were identified which were considered to define the content of co-operative relationships; goal directed behaviour, rewards for each participant, distributed responses, co-ordination and social co-ordination. Marwell and Schmitt suggested that these five elements of co-operation could be combined in various ways to define several types of co-operation. In particular, several of the elements form a logical chain in which each successive element assumes the presence of the previous elements. For example, social co-ordination requires co-ordination *per se*, and both assume that responses are distributed and if participants within a co-operative group gain equitable rewards then it can be assumed that there exists a shared goal.

One of the major activities undertaken by co-operative groups is the clarification and communication of goals. If at the outset agreement can be achieved as to the nature of these goals and the procedures necessary for their attainment, then there exists the potential for co-operation to occur. Sherif and Sherif (1969) referred to an agreed goal whose attainment was dependent on the activities of other group members as a 'superordinate goal'. For example, authors co-operating in the production of a shared document, where one author's contribution is dependent on the work of the other. These are goals that are compelling for the individuals involved, but cannot be achieved by one individual by his or her own efforts. Such work was initially reported by Sherif & Sherif (1953) and later replicated by Blake & Mouton (1962), and by Blake, Shepard & Mouton (1964), for a variety of tasks. The existence of superordinate goals appears to provide a bonding effect within a group. While shared goals are important within the co-operative relationship, their existence does not always imply co-operative behaviour. For example, two individuals wishing to purchase the same property undoubtedly share the same goal, but the success of one party results in the failure of the other. Clearly this will not encourage a co-operative relationship. Deutsch (1968) demonstrated both theoretically and experimentally that group members who are co-operatively interdependent in the service of some tasks tend to be friendlier and mutually more influential and otherwise give evidence of higher cohesion than do similar groups acting in a competitive manner. Superordinate goals developed by participants themselves as members of intact groups are the soundest approach to replacing competition with co-operation (Blake & Mouton 1976).

Co-operation is not a fixed pattern of behaviour but is a changing, adaptive process directed to future results. The representation (and understanding) of intent by every participant is essential to co-operation (Scrivener et al, 1993). Consequently communication plays a vital role in facilitating co-operative behaviour (Oberquelle 1983, 1984). The importance of communication to co-operative behaviour has led some researchers to view communication as a co-operative act in itself. Argyle (1991) made such a claim when he described communication as a process 'where both speaker and listener co-operate in the creation of a joint product'.

Communication within co-operative groups focuses on the identification of shared goals and methods for their achievement. Central to this process is argument, which has the potential to either increase cohesion or fragment a group. The outcome depends on how the group is organised and the level of interpersonal skills of the participants. Argument has the potential to promote uncertainty about the views held by individual group members and can result in an active search for more information, a re-evaluation of knowledge and opinions and, consequently, a greater understanding of the subject areas. Individuals working alone and those in competitive groups do not have the opportunity for such a process and as a result could adversely effect the eventual quality of solution. Evidence provided by Walton, (Walton 1969) supports the advantages of argument during group problem solving. He proposed that co-operation was facilitated by an open and frank exchange of information between parties, whereas competition was characterised by rigid and formal interactions reflected in a rationing of information between participants.

A group must first achieve stability if it is to support and sustain argument among its members. A number of factors have been identified which contribute to the overall stability of a group. These include the following: a mutual respect of the abilities of each of the group members, a history of success associated with that group and finally the existence of equitable rewards for membership of that group. If these factors are present, or the likelihood of their occurrence in the future is high, then a stable relationship can evolve and can be transferred to new tasks. The number of co-operative encounters will diminish hostility within a group and increase the likelihood of co-operative behaviour in the future. Although it should be acknowledged that continued co-operation requires success and that the initial state of a group embarking on a co-operative venture will also effect reaction to failure.

No single method will suffice to induce or maintain co-operation within a group. Although the most effective method for reducing intergroup conflict involves the combination of a number of factors. These include the reduction of threat potential (Deutsch and Krauss 1960), open communication (Shure et al. 1965), exchange of information (content of communication is an important determinant of future co-operation), and finally the existence of superordinate goals (Sherif and Sherif, 1969). Communication plays an important role in co-operation, particularly when it centres on the identification of shared goals that are, in turn, mediated by and through the existence of shared artefacts (i.e. drawings, models or documents). Finally, the extent to which co-operative behaviour is manifest is affected by the type of task, the size of the group, the stage in the task and the environment in which the behaviour takes place.

2.6 Solution Refinement

A principal element of co-operative behaviour during problem solving is the creation of an environment, where solutions can be refined by logical argument and the resolution of different perspectives (Axelrod, 1976). Through these discussions the very essence of the problem is revealed. A number of techniques aimed at facilitating such divergent thinking have been developed, including Brainstorming (Osborn 1953) and Synetics (Gordon 1961). Essential to this view of the co-operative group is the ability of any participant to generate and communicate alternative solutions, as it is these that spark the iterative process of solution implicit in co-operation (Broadbent 1973). Alternatives and partial solutions become the currency of group communication. In short, different but sympathetic beliefs are vital to a successful and productive co-operative relationship. The importance of such a dynamic interaction during co-operative behaviour is reflected in Feyerabend's (Feyerabend 1965) statement that 'progress can only be brought about by the active iteration of different theories'.

In terms of design, Donald Schön (Schön 1983) describes the presentation and acceptance of alternatives as the move from a 'what if' to a decision that thus becomes a 'design node'. Design nodes can be thought of as points of clarity in the mêlée that characterises much of complex problem solving activities. Such nodes are similar to the idea of a 'primary generator' proposed by Darke (1978). Design nodes provide a stable platform with implications for further decisions. Thus there is a continually evolving system of implications within which the designer 'reflects in action'. It is proposed that alternative ideas generated within a co-operative group could act as catalysts and so play an active role in the formation of ideas by changing the context in which participants perceive the problem, thereby providing what Jones (Jones 1970), called a 'greater perceptual span', (Smyth and Clarke 1990).

2.7 Co-operation and its Relationship with Tasks

Co-operation is tightly bound to the nature of the task being undertaken. Certain tasks appear not to benefit from co-operative behaviour. Indeed in such cases the whole process appears unnecessarily complex. These problems are characteristically well defined, with prescribed goals or end states. Their solution entails the identification of the appropriate means of achieving these states (Newell, Shaw and Simon 1967). Once this is found the problem is solved. A common example is the solution of two algebraic equations with two unknown values. In this case there is a known algorithmic method for solution. The aim is to find the values of X and Y by the application of the rules of algebra to the specified equation structure. The goal is clear, to solve the equation for the two variables X and Y and in order to achieve this various algebraic rules and procedures need to be applied. Although this is undoubtedly a complex process, once the equations are solved there is no need for further debate. It should be understood, however, that solving even these problems requires both definition and re-definition of the problem space such that a solution can be proposed. The formation of highly co-operative groups does not automatically provide a panacea for better problem solving in all situations.

Collins & Guetzkow (1964) identified the nature of the task or problem domain as exerting a profound influence on the extent to which the group is, or is not, superior to its individual members working in isolation. For example, tasks which require more than one solution are better suited to a group approach. Thorndike (1938) conducted an experiment to test the hypothesis that the superiority of the group over the individual will be greatest for tasks that afford a wide range of possible solutions. In general the hypothesis was confirmed. While Husband (1940) found that pairs were superior to individuals when working on problems requiring some originality and insight, but not on more routine arithmetic problems.

Tasks which are best suited to co-operative behaviour are best described by the term 'wicked problems' (Rittel and Webber 1972). Wicked problems are characterised as follows: they are problems without a definitive formulation. Secondly, they are problems with no explicit basis for termination, that is, at any time a solution can be further refined.

Finally, solutions that are proposed are not necessarily correct or incorrect, plausible alternatives can always be provided.

2.8 Co-operation: A Panacea for Problem Solving?

Co-operative behaviour within groups during complex problem solving appears to provide a number of advantages over individual working. A number of empirical studies have sought to identify the benefits offered by co-operation. Davis (1969) summarised comparisons of group and individual products and concluded that on most criteria groups are generally superior to individuals but that the existence and degree of superiority depended on a number of task and situational factors. If each person in a group possesses unique but relevant information, and the task requires several pieces of information, then the pooling of this information will allow groups potentially to solve problems that an individual cannot attack successfully. Davis further states that if the emphasis is on achieving a correct, good or early answer, then a group has a higher probability of achieving this aim (other things being equal) than an individual. He concludes by commenting that if errors are costly relative to success, and if the aim is the preservation of group stability, and man hours are cheap, the group affords substantial advantages with regard to task performance, quite aside from any extra advantages such as pleasure in group discussion or social support.

While studying the different problem solving strategies exhibited by groups versus individuals, Laughlin, McGlynn, Anderson & Jacobson (1968) found that during a concept attainment task co-operative pairs typically discovered the concept in fewer steps than did individuals, and also arrived at fewer untenable hypotheses. The basic idea in a concept attainment task is that, over a sequence of trials or over time, the subject learns that some stimulus events belong together and thus are instances of the concept, whereas other stimulus events are not instances of it. In essence, stimulus objects are grouped or classified in such a way that all members of a class have something in common. The task used by Laughlin et al utilised combinations of shape and colour, whereby the experimenter choose an arbitrary concept (i.e. red triangle) and indicated an instance of that concept to the subject. The individual or group then had to identify the concept in the least number of steps. Pairs tended to favour a focusing strategy in attaining the concept, while individuals favoured scanning, a strategy which placed a high memory demand on the user. In terms of group performance, the potential for discussion offered a critical advantage over individual working. While the collective memory of the group offered little improvement to that of the individual, whose memory could be easily supplemented by the use of external aids (i.e. pencil and paper).

An influential series of experiments investigating the nature of co-operative behaviour within problem-solving groups was undertaken by Morton Deutsch (1949a). When contrasting the performance of co-operative versus competitive groups, Deutsch reported a higher degree of production being attained by co-operative groups. Higher output per unit time and a higher quality of proposals. Co-operative groups were observed to co-ordinate division of labour and to achieve better communication among members in order to best utilise resources. Deutsch also judged co-operative groups to invest more effort in maintenance, strengthening, or regulation of the group.

Based on such studies, it is clear that by adopting co-operative working practices, problem solving groups can improve their overall performance. Unfortunately, the adoption of co-operative working practices is not without cost to the group. Co-operation necessitates a group to actively maintain its internal structure. Co-operation leading to success will facilitate such maintenance, but will not act as a substitute.

In contrast to an earlier study by Deutsch (1949b), Davis and Restle (1963) reported that members of freely interacting ad hoc groups rarely re-arranged an optimal interpersonal structure to process the information demanded by a problem. Optimality was measured in terms of speed and accuracy of solution production. They concluded that group performance is rarely at the level of its best member, and thus more often drops below the baseline describing optimal performance. This conclusion holds true even when the task and the circumstances permit a division of labour, the group rarely organised itself so as to exploit the advantages of pooling partial solutions.

The evidence from these studies suggests that if a group is to avail itself of the advantages of co-operation, it must also insure against the cost associated with an increased organisational overhead. Organisational costs rise in proportion to the size of the group and are interrelated with the nature of the task. Implicit within co-operative behaviour is the requirement for a high degree of co-ordination. Axelrod (1984) has stated that 'for co-operation to be at its most effective, the required co-ordination should be transparent to all participants'. Large groups preclude such transparency suggesting that only small groups can ever exhibit co-operative behaviour. Furthermore, in a large group a participant can reasonably expect that the overall effect of individual actions will become less influential as the size of the group increases. Such a dilution, coupled with the necessary organisational overheads suggest that for groups beyond some size, overall co-operation becomes unsustainable, (Glance & Huberman 1994). Successful groups should be composed in such a way as to achieve a balance between the required task expertise and the number of participants.

Co-operative behaviour does not simply occur by bringing together a group of people. The development of co-operation relies on a subtle blend of task related factors coupled with the behaviour exhibited by the group. The studies described in the previous sections serve to illustrate the complexity of co-operative behaviour through their endeavours to identify those factors that induce and maintain co-operation. Undoubtedly there exist certain benefits associated with co-operative behaviour within groups. In particular, when the approach is applied to complex, ill-defined problems. How might such an approach be translated into how we conceive of, design and interact with and through technological artefacts? It is this question that will permeate the research reported within the thesis and will be manifest in a series of prototype systems and their subsequent evaluation. As an initial step toward addressing this question it is appropriate to consider the design of technology from a Human Computer Interaction (HCI) perspective.

2.9 Systems for Experts rather than Expert Systems

Among HCI practitioners it is a widely held belief that the principal design goal associated with the development of technological artefacts is that of user empowerment. How this goal might be achieved preoccupies the majority of HCI research today, and to that extent the research reported here is no different. User empowerment is generally considered to be achievable by one of two means. Either, by enabling a user to better perform an existing task, as measured by some predefined criteria, or by providing new ways that a user can conceive of, and interact with, a task domain.

In the field of software development an emphasis is currently placed on the provision of software based tools to support users in the course of their working practices. Tools, whether computer based or real world, are generally considered to be artefacts that afford the user some advantage during the course of performing a task.

Well designed tools become effectively 'transparent' during use, thereby enabling the user to concentrate on the task at hand, rather than be distracted by the operation of the tool. Characteristic of such tools is their ability to utilise tacit knowledge on the part of the user (i.e. competent practitioners know more than they can say), thereby enabling what is referred to as 'focal awareness', (Polanyi 1973) on the task. In short, a well designed tool becomes an extension of the user's body, (Ehn 1989). The relationship between tool usage and the physical body is a theme that will re-emerge later in the thesis. In particular, during the case studies of design tool usage, which will be reported in Chapter 5. Similar principles with respect to the mind have been proposed for the design of software tools, as illustrated by Rutkowski's (1982) statement that '... the user is able to apply intellect directly to the task; the tool itself seems to disappear'.

The design of software tools has been greatly influenced by the conception of appropriate interaction paradigms, in particular the model world metaphor (Hutchins, 1989). In a system built on the model world metaphor, the interface constitutes a world wherein the user can perform actions that are reflected by changes in system state. Central to this perspective is the explicit representation of the user's world of interest and the tools that populate that world. An example of a tool based interaction paradigm based on this approach is direct manipulation.

The principle underpinning direct manipulation has been described by Hutchins (1989) as an attempt to bridge the gulf between user intention and action. He introduces the term 'referential distance' to refer to the extent that the user's understanding of the meaning of an expression is similar to their understanding of the form of that expression. Direct manipulation can be characterised as an attempt to reduce the referential distance by engendering the perception of a direct linkage between user action and object behaviour. Thus presenting the user with the illusion that they are interacting in an environment which reflects their task goals and intentions.

While direct manipulation enables the user to more easily interact in the context of a task it is not without associated problems. For example, the performance of repetitive operations is time consuming for the user and would probably be better achieved through a symbolic description of the task that is to be accomplished. Direct manipulation interfaces aim to amplify the user's knowledge of the domain by allowing them to think in familiar terms rather than those of the medium of computation. But if designers are restricted to only building interfaces that allow the user to do things that they already can do and to think in ways that they already think, then the most exciting potential of new technology will be missed. In short, to provide new ways to think of, and interact with, a task domain.

With this aim in mind, a number of software designers have moved away from the traditional tool based approach and have developed prototype systems that attempt to actively perform task related processes on behalf of, and in conjunction with, the user. These systems perform relatively simple processes either automatically or under instruction by the user. For example, sorting new mail into folders as it arrives or automatically reminding the user of deadlines (e.g. OBJECT LENS, Crowston & Malone 1988), facilitating interaction with databases (e.g. GUIDES, Laurel et al. 1990) or attempting active participation during interaction with the Macintosh OS (e.g. EAGER, Cypher 1991). The distinction between process and tool based approaches is not new. Indeed, such a shift was predicted by Alan Kay when he stated that, tool based... 'manipulation is still vibrantly alive, not exhausted. But it is time to consider management of intelligent computer processes as an inevitable partner to tool based work and play', Kay (1990). Such a partnership will only be mediated by the design of appropriate user interfaces. The idea of combining both the process and tool based approaches would appear at the outset to be impractical as the concept of processes which perform actions on behalf of the user is in contravention to the basic principle of direct manipulation. The process approach introduces a level of indirection between the user's task related intentions and actions. No longer will the user solely interact with tools, but they will also interact with processes that are using those same tools in order to perform actions for the user.

The agent based systems of the early 1990s raised certain issues, in particular concerning the update of their knowledge bases. For example, how might a system such as EAGER continue to proffer assistance to a user without having the ability to learn new strategies? This, in turn, raises the question of who, or what, will act as the source of new knowledge. Logically it should be the user, but such a strategy would result in the creation of an agent that embodies the habits of the user. Such a characteristic, whether software or otherwise, is hardly a desirable characteristic in such circumstances. As a direct result of this, the initial wave of agent based systems made little impact until, that was, they returned in the guise of Web based recommendation systems. Such an approach is exemplified by the work of Pattie Maes and her group at the Massachusetts Institute of Technology (MIT). As their name suggests, recommender systems seek to proffer advice to the user about certain topics. For example, particular music based on the tastes input by the user (e.g. RINGO, Maes et al, 1997) or relevant web pages based on the interests of a user (e.g. LETIZIA, Lieberman, 1995). A variation on this theme is the development of agents for expert location (Vivacqua, 1999). In this case agents help the user to locate specific experts related to given problems. Such a system relies on experts to 'advertise' their services, which is an interesting approach to the generation of the underpinning knowledge base associated with the system. The interesting point with respect to knowledge update is that because such systems are designed for use by multiple users, then information can be gathered from a variety of sources. Indeed, it is such diversity that provides recommender systems with longevity. A similar strategy will also be seen to address the short comings of critic based systems which are introduced later in the chapter. Gathering information from a wide variety of sources and then aggregating it in order to update a dynamic knowledge base is an interesting strategy and is only made possible by the widespread proliferation of the World Wide Web (WWW).

If technology is to empower the user with both software based tools and also software based processes which can undertake task related activities then appropriate interaction paradigms will have to be sought. Such systems, if they are to effectively empower the user by augmenting human performance, must be designed not only to complement existing user task skills but, it is proposed that they must also support existing human social skills. This idea is not new. Indeed Srinivasan and Dascher (1977) stated that, 'we need to develop a language structure that will embrace a broad diversity of the kinds of communication that users normally use'. What is not obvious is how such aims might be translated into usable procedures to assist software designers. A possible route, explored in this chapter, might be to utilise the research within psychology in order to provide a clearer picture of how humans co-operate. The work reported here is not seen as a solution in itself, but as another perspective from which to view the problem of how to design more usable computer systems.

This chapter explores the theme that a more comprehensive understanding of the nature of human interaction could inform the design of future systems. In particular, the dynamics associated with dyads and small groups, as they appear to map onto human-system interaction. Before embarking on such a venture it is necessary to consider whether the goal of transforming the computer from passive tool to active partner is indeed useful or desirable.

The sheer complexity of many of the tasks supported by current systems has resulted in an increased cognitive load being placed on the user. Indeed the situation has been exacerbated by the requirement for the user to conform to the interaction style dictated by the computational medium. While direct manipulation enables the user to achieve a closer coupling with the domain, it fails to reduce the complexity inherent in the task. If, on the other hand, the system were to enable a more equitable division of labour, such that repetitive or computationally intensive aspects of a task could be assigned to the system, the result would be to release the user to engage in more qualitative aspects of the task. It is proposed that fundamental to the goal of user empowerment is the realisation that technology should work in partnership with the user, and that each brings to the domain different but necessary skills. The designers of future technological systems should aspire to release the creative potential of the user by relieving them of those aspects of the task better suited to the technology, rather than by the provision of tools whereby the user can better perform those tasks. Enabling the performance of tasks that a user has no desire to undertake in the first place is not empowerment. In their characterisation of the design of cognitive tools for decision support Woods et al (1990) drew a similar distinction between cognitive tools as 'prostheses' and as 'instruments'. They suggest that the cognitive tool as prosthesis paradigm attempts to replace or remedy a perceived deficiency in the user, thereby casting them into a passive relationship with the system. While in the case of the cognitive tool as instrument paradigm an attempt is made to utilise the existing skills of the user as a resource to be used in the pursuit of a goal, resulting in an active role for the user. This distinction is brought sharply into focus by viewing human computer interaction as a co-operative partnership between the human and the computer and by the explicit acknowledgement that each bring different but necessary skills to the task domain. In short, those systems designed to maximise the synergy of the human computer partnership during complex problem solving.

The next section will outline some nascent design guidelines for the design of co-operative systems and, more generally, Computer Supported Co-operative Working (CSCW) systems. Co-operative systems are those which seek to design an interaction with the user that is informed by co-operative behaviour. CSCW systems, on the other hand, aim to support co-operative working between individuals or groups, who are either geographically distributed or collocated, via the medium of technology.

2.10 Implications for the Design of Co-operative Systems

It is important to realise that the findings presented in the previous sections refer to co-operative behaviour between humans and, as such, will require re-interpretation in order to identify a set of issues pertinent to the design of computer based systems to support co-operation. This section will summarise a number of issues, based on the research previously described, which are pertinent to the design of systems that seek to harness the advantages of co-operation. While the focus of the research remains technology that empowers the individual, the nature of the approach means that a number of the issues identified are also relevant to the design of CSCW systems.

Perhaps the most far reaching conclusion is that the technique of co-operative problem solving is not generally applicable across all task domains. Certain tasks, principally those that have a single correct solution, do not appear to benefit from a co-operative approach. Indeed, the application of co-operation to such domains could well result in a significant reduction in productivity. The class of tasks which would appear to benefit most directly from co-operative endeavours are those where multiple solutions exist and the difficulty lies in determining the most appropriate, given a set of constraints and requirements. In terms of the application of a computer based co-operative system, it could manage the constraints and requirements associated with the task, while the user can explore the 'problem space' safe in the knowledge that the system will alert them if any transgressions occur. In such a scenario user empowerment would be enabled by the provision of an environment wherein the user might realise their creative potential through the freedom to explore solutions and not be encumbered with the need to engage in routine elements of the task.

Communication and co-ordination were identified as being vital to the development and maintenance of a co-operative relationship. In terms of design of co-operative systems these features can be related to specific stages of a co-operative interaction. Firstly, the communication necessary for the identification and agreement of shared goals, and secondly, the methods whereby alternative solutions can be presented to the user without causing distraction from current activities. As stated earlier co-operation requires that task related goals be shared among the group members. The critical problem, which remains to be solved, is how a user might successfully communicate a goal to the system, at the required level of detail, and in a terminology suitable to the computational medium. Indeed, once in such a position, many designers would claim to have solved the problem. In Chapter 3 a prototype co-operative system P0 will be described, including a mechanism for the expression of user goals, which is based on a visual programming paradigm.

A co-operative relationship requires co-ordination and communication among the participants. Without either explicit or implicit co-ordination the relationship will break down. Similarly, the design of co-operative systems will require that communication between the human-computer partnership should exhibit a comparable degree of co-ordination. It is vital that the system designer realises the importance of not only the content of the communication, but also the context of that communication. How and when alternative solutions are presented to the user in the context of the task is vital in engendering a stable co-operative relationship. Communication is pivotal in the formation and maintenance of co-operation between humans and, if computer based co-operative systems are to enable the necessary level of communication, then the design of the interface will be crucial. To this end it is desirable that the user has the ability to both interrogate and update the system.

If it is accepted that the generation of alternative solutions is a viable mechanism whereby a system could take an active role during problem solving, then a number of further design issues must be considered. For example, what knowledge must be embedded in the system and how will it be represented. What form will such knowledge take? For example, might it be case based and if so will the cases be those of the user? If the answer is yes, then the result will ultimately be to mimic the user's expertise and reduce the effectiveness of alternative solutions to act as a spur for the user's creativity. In a similar manner to co-operation among humans, do systems that are designed in this way have a 'limited shelf life' before they are seen to be producing similar solutions to all problems? Both the representation and manipulation of knowledge will remain important issues throughout the research reported in the thesis.

A further set of issues has been identified which relate directly to the design of CSCW systems. These are systems that support co-operative working between humans by and through the technology. The allocation of rewards among group members is considered to be important in the maintenance of a co-operative group (Argyle, 1991). If rewards are deemed by members of the group to be unfair then the result will be a breakdown in group structure. Currently, CSCW systems rely on the implicit notion that all participants receive the same reward that of engaging in a joint problem solving group. As group membership becomes more heterogeneous then the receipt of rewards will have to be made more explicit. Whether this can be achieved solely via communication is open to debate. The Object Lens system (Malone et al, 1987) is an interesting case in point. This was a system build around a sophisticated set of mail filters which enabled certain rules to be fired on receipt of mail messages (i.e. to alert the user if a particular individual mailed them). The system failed, in the main, because of the effort required for the sender of a mail message to complete all the extra fields required by the system. The burden of effort was placed on the sender, while all the benefits were accrued by the recipient. This inequity of reward was central to the failure of the system.

A further factor is that of group size and its effect on the decision making process (Glance and Huberman, 1994). The results suggest that an optimal number of participants exist for a problem solving group, notionally between 5-7 people. Below that number and information can be lost owing to the removal of redundancy, while above that number the organisational overhead, together with the resulting formalism, will reduce the likelihood of generating novel solutions. Finally, the issue of anonymity within a group is well documented together with an increased likelihood of generating more extreme solutions. Taking this result in conjunction with the increased anonymity caused by computer mediated communication then the potential for high-risk decisions should not be ignored.

To conclude, user empowerment will only ever be fully achieved by the design of systems that work in partnership with the user. The study of human co-operation has revealed a number of research issues that must be addressed in order to achieve this goal. The remainder of this chapter will outline a number of systems that have sought to harness certain advantages associated with co-operative behaviour. Collectively these systems are referred to as Human Computer Collaboration (HCC) systems (Terveen, 1995).

2.11 Human Computer Collaboration Systems

In general there are two main approaches to the problem of designing human computer collaborative systems. Firstly human emulation which comes from an Artificial Intelligence (AI) tradition and secondly, human complementary from the HCI tradition. The former addresses issues such as planning, discourse and user modelling, while the latter addresses such things as interaction, agents and adaptivity.

If technology is to successfully collaborate with a user then a key problem that must be overcome is the communication of intent. This raises an interesting problem, which is the degree of articulation of the problem that is required by the system in order that it might collaborate with a user. In order to describe a problem at the level of detail required by most HCC systems it is necessary to have solved the problem in the first place. The human emulation approach to this problem has been to focus on domain specificity and the creation of a language through which users express their goals. Key to such a layered approach is the support for incremental expression of goals. The human complementary approach adopts a more asymmetric view of the relationship between human and computer through the explicit acknowledgement that each bring a different set of skills to bear on a problem.

2.12 Strategies for Dealing with Goals

Across the approaches that have been discussed three main strategies exist for dealing with how the user communicates their goals to the system, or indeed explores goals as a means of better understanding the problem. Firstly, AI based plan recognition, where the system seeks to ascertain a user's plan based on their behaviour while interacting with the system. One can envisage such an approach working within a highly constrained domain where only a limited number of actions are available to a user, but in reality the complexity of most problem solving tasks must bring into question such a strategy. The second approach has been to hardwire a representative set of domain goals into the system. While such a strategy enables the study of a prototype HCC, it is not a viable long term solution. The third strategy that has become popular has been to represent goals and plans at the level of the interface and allow users to specify them as required. As will be seen in Chapter 3, a similar approach to goal formulation was adopted by the prototype P0.

2.13 Visual Objects as a Mechanism of Communication

One of the issues raised by research into HCCs is how to manage communication between the user and the system, in such a way as to offer timely and factually pertinent advice without constant interruption. One solution has been to modify the display as a means of communication rather than generating traditional text messages. Examples, of systems which use such techniques include HKE (Terveen, 1993) which uses colour, shading and fonts and DETENTE (Wroblewski et al, 1991) a system which reported on the status of the management of tasks using similar techniques.

In terms of the advice that critic systems offer users Nakakoji and Fischer (1995) describe these in terms of three levels; firstly messages indicating potential problems, secondly indices into an argumentation database generated from analysis of the current design solution, thirdly access to previous designs deemed relevant to the current design. Indeed empirical evidence suggests that system assistance is useful even if designers disagree with the advice proffered by the critic - the act of articulation as to why the user likes or dislikes the advice is a key step towards understanding. The ensuing dialogue that occurs around and because of the generation of an alternative solution, whether it is with the 'self' or with others is, it will be contended, as important as the process of generation itself. This point is supported by a study of radiologists conducted by Rogers (1995) into their interpretation of chest x-rays using a prototype support system. The system and the user could offer interpretations, hypotheses and suggestions. The study showed that using the system increased solution quality.

2.14 Adaptation through Collaboration

This approach is based on the idea that one can learn about a problem through an attempt to articulate that problem. Learning can take place on the part of the speaker and the listener. The critiquing paradigm offers a form of learning to users and potentially the computer partner. Indeed the process of critiquing has the effect of potentially exposing the partner to new knowledge. Intelligent tutoring systems are an example of systems that have sought to harness this potential through collaborative learning. The approach to learning raises the issue of how a co-learner embedded in a system could successfully keep pace with the human learner. Examples of systems which have sought to address this issue include, Issue Based Information Systems (IBIS) (Kuntz and Rittel, 1970) which seek to structure argumentation, Object Lens (Malone et al 1987), speech spectrograms (Candy et al, 1993) both of these systems provided mechanisms for end user modification and as a consequence learning about the specifics of the domain. Finally, the work of Maes (1994) into the behaviour of agents that seek to learn user preferences and thus tailor information to their specific needs as embodied in the recommendation systems discussed in Section 2.9.

2.15 Critic based Systems

These systems monitor user action in a computational environment and offer advice. Critics compute their advice by using a domain knowledge base to examine the actions users perform and the products that they create. In the critiquing interaction, humans select goals to pursue, attempt to achieve these goals and retain control of the interaction. Whereas in the more formal planning strategies adopted within human emulation the user can be perceived as responding to the structure imposed by the system. Critics seek to detect potential problems in the user's problem solving and suggest solutions, propose additional relevant issues to consider and automatically perform routine or low-level aspects of the problem solving. Users can then evaluate system critiques and decide on an appropriate response. Critics do not necessarily solve problems for users, rather their role is to stimulate and inform user problem solving. Critics are not expert systems. In the tradition of co-operation and collaboration they seek to promote a reasoned argument in which issues are made explicit and in which alternatives are considered.

Critic based systems can be thought of as those which first cause the user to maximise the level of falsifiability of his statements and then proceed to check if errors exist. A good critic program doubts and traps its user into revealing his errors (Silverman, 1992). It then attempts to help him make the necessary repairs. In general two sources of input exist in critic systems: firstly, a description of the problem (e.g. design requirements) and secondly the proposed solution to the problem (e.g. a design). It is the second input that distinguishes critics from expert systems, as it is the norm that such systems compute their solutions that are then offered to the user as output. For a critic, the solution is part of the input process, while the output is the criticism.

Critic based systems contain two main components: a differential analyser and a dialogue generator (Silverman, 1992). The former seeks to infer the user's goal through a comparison between the user's task result and one produced by an internal 'expert module'. This usually comprises a domain specific rule base. The dialogue generator receives output from the analyser and seeks to parse these into a meaningful critic for the user. Some critic based systems have utilised user models as a means of tailoring output to the specific needs of the user. In terms of interaction it is important to recognise that effective critiquing requires a process, not an event. There must be a mutual exchange of viewpoints, not a one-sided test. The critic needs interactive skills, not sermon-giving. The critic becomes an interactive process. It requires mutual exchange, a search for truth, and a dialogue in which both parties can benefit not just the recipient of the criticism.

Critic based systems are the closest in spirit to the prototype system P0 that will be described in the next chapter. In order to explore this approach the remainder of the section will summarise some of the more influential prototype critic based systems.

2.15.1 The Attending Critics

A body of research (Miller, 1983) which has contributed to the thinking in the domain of critics. For example, one of the findings associated with this work was that user goal interpretation was highly domain specific. Furthermore, that there exists a trade-off between the level of sophistication associated with the analysis of goals and the number of potential solutions to a given problem. The more solutions the greater the sophistication of the analysis required. An attribute of Miller's critics was that the system selected between alternatives based on the understanding of the user expressed requirements.

2.15.2 ONCOCIN

Developed by Langlotz and Shortliffe (1983) this system originally started as an expert system for the diagnosis of cancer problems in a clinical setting. Testing revealed user acceptance problems at the level of the interface. The transition of the human expert from data gatherer and a recipient of the system's solution to the generator of solutions, which may or may not be critiqued by the system, addressed user's concerns. The system used a series of hard coded rules from which critiques were made.

2.15.3 CRITTER

This critic evaluated digital circuit designs for deficiencies (Kelly, 1984). The system had a rule base of typical oversights on the part of the human designers. These were used as a basis from which the system sought to identify weaknesses in the user's solution. A dialogue was then generated with the user which described the problem, but also sought to create a more user controlled dialogue - where different levels of detail were available until the user was satisfied.

2.15.4 COPE

The design of a generic critic shell that sought to be theory driven rather than practice driven as so many of its predecessors had been (Silverman 1990). The aim was to build on the work of Miller and to address the need for empirical evidence as to the effectiveness of critics - early studies of COPE suggest a positive contribution to problem solving. Indeed, this work has contributed to the design and development of TIME, a critique system which supports decision paper writing in the US Army (Silverman, 1991) one of the largest critics of its time and built within the COPE shell.

2.15.5 University of Colorado Critics

This approach develops Illich's (1973) concept of convivial tools, that is tools 'which give each person who uses them the greatest opportunity to enrich the environment with the fruits of his or her vision'. Fischer (1992) argues that to turn computers into convivial tools requires that people can use, change and enhance their tools and build new ones without having to become professional level programmers. A central facet of these systems, he argues, is their critiquing capability. These offer advice and information by supporting 'reflection in action' (Schön, 1983), thereby allowing users to explore, what Fischer refers to as, the contextualised argumentation and design rationale associated with their actions. Using design environments, designers create artefacts that serve as externalisations of their thoughts (Bruner, 1996). These artefacts can be critiqued by computational critics, thereby increasing the 'talk-back' of the design situation (Schön, 1983).

Fischer (1991) believes that critiquing is a major activity of a co-operative problem solving system. Critiquing is characterised as the presentation of reasoned opinion about a product or action. Such systems seek to point out errors and sub-optimal conditions. The systems developed by Fischer and his colleagues relate to a variety of domains. Some examples will be provided below.

2.15.5.1 Activist

A critic in the form of an active help system for a text editor (Fischer et al, 1985). The system monitors user behaviour and attempts to infer user goals from observed actions. The system then matches the user's actions to plans in its knowledge base that accomplish the same goals. Based on this model Activist offers advice. In many ways the underlying mechanisms of Activist are similar to that of EAGER (Cypher, 1991). EAGER attempted to determine patterns of inappropriate behaviour while the user performed tasks using the Macintosh OS, once discovered the system offered advice.

2.15.5.2 LISP Critic

A system designed to support programmers (Fischer, 1987, Fischer and Mastaglio, 1989). Specifically, it sought to improve coding practice and provide a mechanism whereby users could acquire programming knowledge. Interaction with the system was passive, in so far as it was always invoked by the user. It utilised a minimalist explanation strategy so as not to adversely impact on the user's performance of the task and it also incorporated a user model in a bid to tailor the critiquing information.

2.15.5.3 FRAMER

A system designed to assist programmers with the development of user interfaces in LISP machines (Lemke, 1989, Lemke and Fischer, 1990). The presentation of critiquing information was more overt in this system than in the LISP Critic as evaluation of that system revealed that advice was, in general, taken too late by users.

2.15.5.4 JANUS

For the purpose of completeness this system will be described briefly here, but due to its nature it will be dealt with in more detail in Chapter 4. JANUS is a design environment that is based on the critiquing approach and allows designers to construct residential kitchens (Fischer, McCall and Morch, 1989). JANUS contains a critiquing component with knowledge about building codes, safety standards and functional preferences. Based on this understanding the system signals breakdowns in the current design. These are linked to the argumentation element of JANUS which provide the designer with a more detailed analysis of the critique, if required. JANUS is without doubt the closest in spirit to the prototype P0 that will be described in the next chapter. But what makes P0 distinct from JANUS is that rather than offering a critique of a design solution, it attempts to use that solution as a means of generating an alternative solution that is intended to act as a catalyst for design creativity.

2.15.5.5 KID

The Knowing in Design (KID) system introduces a reflexive quality when used in conjunction with the JANUS system. This was achieved by enabling designers to explicitly articulate previously tacit domain knowledge via the technique of critiquing (Nakakoji, 1997).

The research conducted by Fischer's group at the University of Colorado is most notable for being the first to embed critics into complex domains. The overarching aim is the design of systems that enable users to interact successfully with ever more complex environments. In a similar manner to the agent based systems discussed earlier, these systems reached their zenith in the early 1990s. Once again the problem was how to successfully maintain and update the knowledge base associated with a critic system. For example, the initial critique of a solution may identify particular problems, but once a user has become aware of these, how useful is the critic based system? Without the ability to update the knowledge base that underpins the critic it will be destined to have a very short period of usefulness. One solution to this problem has been explored by the work of Fischer, in particular his Domain Oriented Design Environments (DODE) approach.

2.15.5.6 Domain Oriented Design Environments (DODEs)

This approach to the provision of design environments is based on the assumption that domain knowledge is activated and constructed on an ongoing basis during actual problem situations. The concept of active domain construction acknowledges that domain models do not exist *per se*, but that they are socially constructed and evolved (Lave, 1991) by communities of practice. DODEs aim to create environments whereby individuals can engage in creative activities with the help of culturally provided tools and artefacts. This will lead in turn to what Fischer (1999) refers to as 'social creativity'.

2.16 Summary

The literature review contained within this chapter illustrates the diversity of findings with respect to co-operation. Within such diversity a number of key attributes can be identified as central to the creation and maintenance of co-operative groups. These are as follows:

- the existence of shared goals;
- the ability to communicate via an agreed language;
- the ability to generate alternative solutions as these both mediate and structure the co-operative relationship.

The next chapter will describe the design and development of an initial prototype system P0, in particular, the attempt to articulate the attributes outlined above.

3 Prototype P0 – A Study of Human Computer Co-operation

3.1 Overview

This chapter will introduce the following themes:

- the rationale underpinning the prototype;
- a description of the components of the prototype;
- an introduction of design as a task domain;
- an implementation of the prototype;
- an evaluation and discussion of the prototype.

3.2 Introduction

This chapter will introduce a prototype system P0. The aim of the work is to investigate whether the attributes of co-operative behaviour, identified in the previous chapter, could be successfully transformed into guidelines which inform the design of technological artefacts. Furthermore, throughout the design and development phases of the prototype, to study how such attributes would manifest in terms of interaction with such technology. Design, specifically office layout, was selected as a vehicle by which to explore the impact of co-operation in a task based scenario. The prototype, which became known as the 'co-operative machine' incorporated three main components: goal orientated working, a mechanism for the generation of alternative design solutions and an agreed definition knowledge base. The prototype was evaluated by student designers and their feedback, together with the thoughts of the author, are reported at the end of the chapter.

The development of the 'co-operative machine' marked the zenith of co-operation within the research. From that point on a change in emphasis took place and the study of computer based support of the early phase of design began to assume an increased importance within the research. The description of prototype P0 is included within the thesis as it is the contention that it played a formative part in shaping both the approach adopted in the later part of the research and the design and emphasis of the consequent prototypes P1 and P2. This can be seen in firstly, the tool orientated focus of the case studies of design, and secondly in the emphasis on alternative solution generation through rule manipulation which will be seen in the later prototypes.

The means by which to update the knowledge base of the 'co-operative machine' raised similar issues to those reported by the developers of both advice based and critic based systems. Indeed, what is interesting are the solutions adopted in each case, with the advice and critic systems moving towards a more collective approach whereby many individuals contribute to the upkeep of the knowledge base. Examples of this strategy can be seen in Fischer's DODEs (Fischer, 1998) and Maes's Recommender Systems (Maes et al, 1997). The strategy adopted by the research reported here is that of a grammar based approach to the generation of alternative design solutions, this will be reported in Chapter 7.

3.3 Introduction to Prototype P0

The aims of the prototype system, which is described in this chapter, are twofold. Firstly, to explore the generation and presentation of alternative solutions within a design task. Such alternatives are considered to be fundamental to a co-operative approach to problem solving both in terms of articulation and hence understanding of the problem. But also the ability of alternatives to structure the problem solving process. It is through such artefacts that agreement is achieved. Without such tangible instantiations the shared understanding, so critical to co-operation, would undoubtedly be more difficult to achieve. In a similar vein the second aim of the prototype system is to provide the author with such a tangible instantiation of some of the concepts thought to underpin co-operative behaviour. This enables both a dialogue with the self concerning co-operation and in particular the role of alternatives, but also provides a vehicle with which to communicate with colleagues. The reflexive nature of this relationship provides an integrity to the design.

A factor that became apparent during the work described in the previous chapter was that co-operation is a complex phenomenon. This implied that the original conception of a co-operative interface was, in reality, overly simplistic and that any implementation which sought to utilise aspects of co-operative behaviour would have to develop certain underlying software as well as the interface itself. The nature and extent of these changes during the design and development of what was now termed a 'co-operative machine' will be the subject of the remainder of this chapter.

Co-operation is viewed as an active process. A machine that incorporates this technique must overtly participate with the user during a task. It is contended that a co-operative machine, while remaining focused toward an expressible goal state, will prompt the human partner to adopt a more divergent style of thinking during problem solving. Furthermore, it is suggested such interaction will foster a greater interdependency between the human and the machine and, as a consequence, increase the quality of solution and encourage greater user satisfaction.

A principal element of co-operative behaviour during problem solving is the creation of an environment, where the refinement of solutions can be based on logical argument and the resolution between differing perspectives. It is through these discussions that the very essence of the problem is revealed. Essential to this view of the co-operative dyad is the ability of either party to generate and critique alternative solutions, as it is these which spark the iterative solution process implicit within co-operation (Broadbent, 1973). In short, different but sympathetic beliefs are vital to a successful and productive co-operative relationship. The importance of such a dynamic interaction during complex problem solving behaviour is reflected in Feyerabend's (Feyerabend 1965) statement that 'progress can only be brought about by the active iteration of different theories'. Although recognised as only a facet of the complex relationships involved in human-human co-operation, the generation of alternative solutions and the consequent communication that surrounds them was felt to provide a starting point toward representing the co-operative relationship between a human and a machine.

The focus of the work outlined here is to develop a single-user co-operative mechanism where the generation of a satisfactory solution could be enhanced by a machine which has the capability of generating alternative and supplementary information based on a solution proposed by the user. Any attempt to harness the potential of human-human co-operation and apply it to Human Computer Interaction (HCI) will result in the need to view the machine as an active agent and not purely as a provider of information on request.

The contention is that such machine generated alternatives could act as catalysts and so play a more active role in the formation of ideas through changing the context in which the user perceives the problem, thereby providing what Jones (Jones 1970) referred to as a 'greater perceptual span'.

3.4 The Underlying Mechanisms of a Co-operative Machine

The empirical and observational studies of co-operative behaviour, described in Chapter 2, indicate a number of factors that both induce and maintain co-operation between humans during problem solving tasks. This raises the problem of how best to translate what are essentially behavioural characteristics into mechanisms that could be successfully represented within a machine.

Three factors were selected on the grounds that they reflect the underlying processes of co-operative behaviour. The factors were, firstly, the existence of superordinate goals (Sherif and Sherif, 1969), referred to as Goal Oriented Working. Secondly, a model that contained knowledge about the specific task domain and would thereby represent the knowledge of the computer partner, referred to as a Partner Model, and finally a language common to both the co-operating parties, referred to as the Agreed Definition Knowledge Base. Several factors associated with co-operative behaviour, for example the role of social goals as a reward mechanism for undertaking co-operation, are considered to be specifically human traits and were discounted as inappropriate to human computer co-operation.

Although acknowledged as representing only a subset of the complexity of behaviour displayed during human-human co-operation, it was felt that a machine representation of goal oriented working, a partner model and an agreed definition knowledge base would provide an initial architecture from which to study human computer co-operation.

3.4.1 Goal Oriented Working

If a co-operative dyad is to achieve success, be it either human-human or human computer, there must be an agreement, which is formally stated at the outset of the interaction, as to what is the goal to be accomplished. Two parties working toward different or conflicting goals will never achieve full co-operation, although two competitors may inadvertently co-operate. For example, take the scenario where three rival countries A, B and C are in conflict. If A attacks C, this action results in C re-deploy troops away from B in order to defend against A. While A and B remain rivals, the actions of A could be interpreted as co-operative toward B. It is essential in co-operation that the co-operating parties, firstly, know what the desired goal is and, secondly, work towards attaining it.

A goal may be defined as the intended state of an object or the intended relation between two or more objects (Sherif and Sherif, 1953). The action of achieving the goal is directed toward goal objects that may either be physical or virtual and can result in their creation, elimination or modification. Each goal object has attached a number of attributes, such as colour or dimension, which may be altered in the act of achieving a goal. For example, the goal of sharpening a pencil can be restated in the form of, the goal is to have pencil in a sharpened state. In this case the goal object is the pencil and the achievement of the goal will result in the attributes of sharpness and length being changed. Figure 3.1 represents diagrammatically the autonomous agents of human user and computer communicating and working toward achieving a goal. In this case it is envisaged that interaction between the user and co-operative machine will initially centre on the generation of a shared understanding of the current goal, as represented by an object state, or a set of objects. Once this has been achieved, the two work towards a

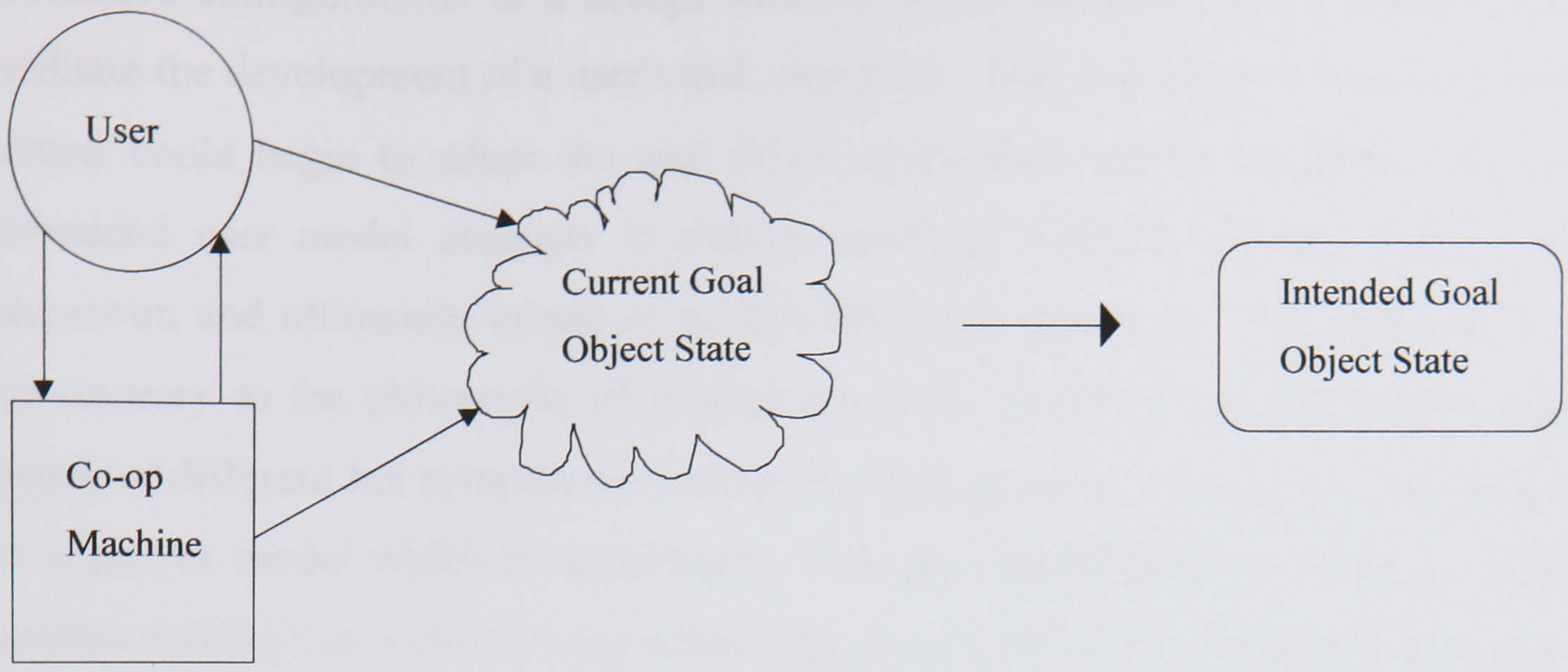


Figure 3.1 Representation of Goal Oriented Working

strategy which will successfully transform the initial state into the intended goal state. This is usually achieved through the manipulation of the object set.

3.4.2 The Partner Model

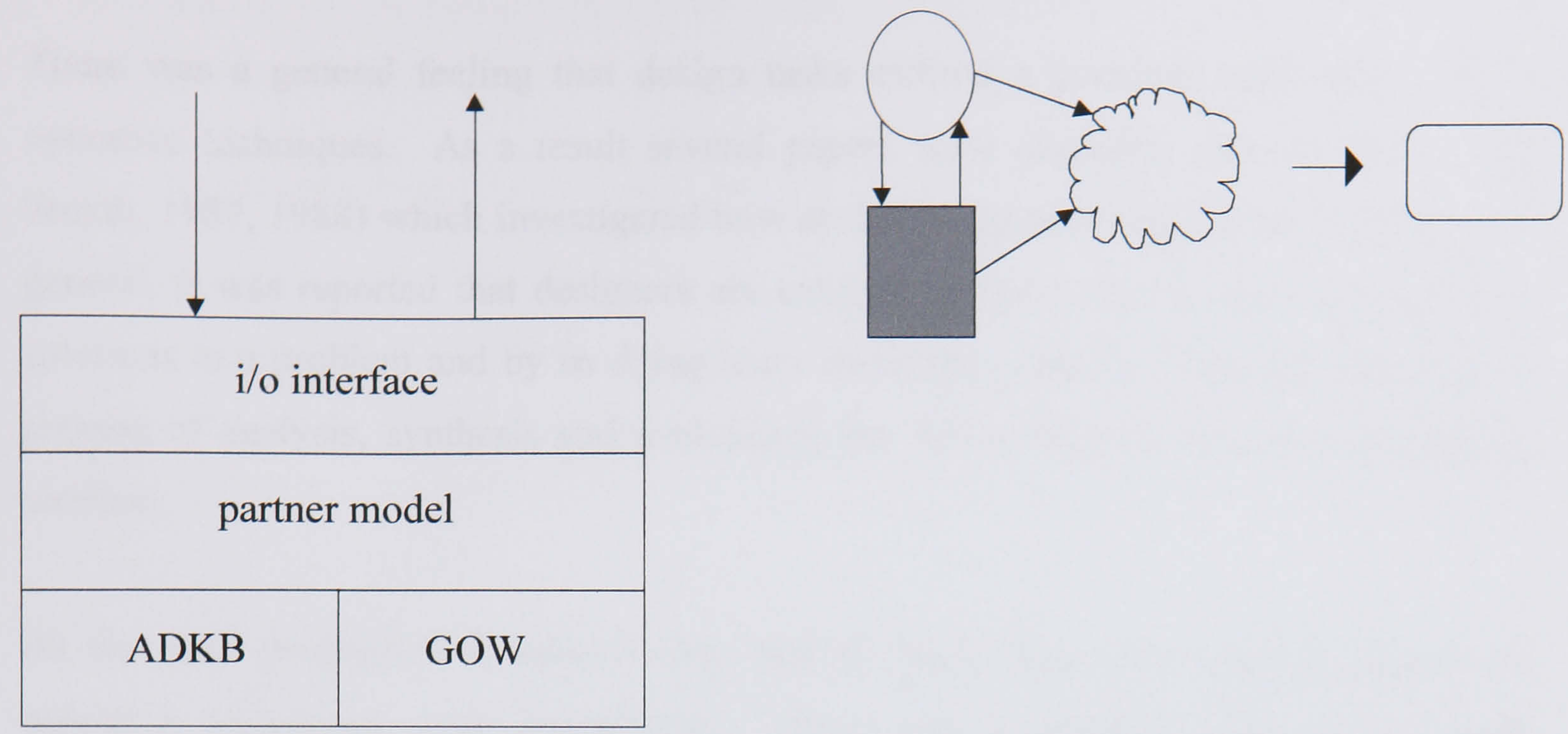
The ability to generate alternative solutions is an important strand in the complex processes exhibited during co-operative behaviour. In order to represent an equivalent mechanism it is necessary to construct a model, consisting of domain specific rules, which has access to a knowledge base common to both the machine and user. The term adopted for the knowledge base is the Agreed Definition Knowledge Base, (ADKB). By applying the model's rules to the ADKB and communicating the result to the user, it is hoped to reflect the process of alternative solution generation as observed in human-human co-operation.

In essence, the co-operative machine requires a model, referred to in this case as the partner model, to both generate alternatives and to facilitate interaction with the user. The partner model is essentially different from an embedded user model, in that it possesses similar domain information to the user, but does not necessarily reflect the working style of the particular end user. The facility to query the partner model rule base is essential if the user is to comprehend the processes leading to the alternative solution. It is only through such understanding that the user might begin to incorporate the partner model's techniques within his or her own design solution strategy. Communication of alternative configurations of a design solution within an interactive environment might facilitate the development of a user's task expertise. That is, during interaction the human partner could begin to adopt the task skills represented within the partner model. An embedded user model attempts to extract concepts exhibited by the user during the interaction and ultimately mimic or predict the user's response. This situation is felt to run contrary to the philosophy of human computer co-operation which emphasises the benefit of different but sympathetic viewpoints during problem solving. The requirement for a partner model which is autonomous from the user reflects the essential difference between entities that makes co-operation such a powerful technique in problem solving.

3.4.3 The Agreed Definition Knowledge Base

Central to co-operative behaviour is the ability of either party to communicate the current state of the interaction. What is important is that both the co-operating parties share the same object definitions. This factor is emphasised during human-human co-operation where a large amount of time is concerned with the mutual identification and agreement of terms of reference to be adopted during the process. The definitions do not have to remain static as long as changes are agreed by both parties. If a co-operative machine is to be fully developed it must provide a sufficient breadth of communication to enable the interactive updating of the shared knowledge base.

Figure 3.2 provides a diagrammatic representation of the three mechanisms which will form the basis of the initial prototype system P0.



ADKB – agreed definition knowledge base

GOW – goal orientated working

Figure 3.2 Schematic Representation of Prototype P0.

3.5 A Co-operative Task Metaphor

At the outset of the research there was an implicit belief that the goal of the work should be to produce general purpose co-operative mechanisms. The idea being that, in principle, co-operative techniques and their associated advantages could be applied to any task. In principle this idea posed little or no real problems during the early discussions as to what did and did not constitute co-operative behaviour. Two potential task domains were initially considered. These were highway design and electronic circuit board design. Although useful as a focus through which to express early, ill formed ideas, it soon became clear that the knowledge representation overhead associated with these task domains was beyond the timescale of the research, if they were to support rudimentary co-operation. In retrospect this decision seems somewhat ironical. In fact an investigation of highway engineers (Clarke et al, 1986) revealed that responsibility was not held by a single person but by a group of individuals each possessing specialist knowledge.

There was a general feeling that design tasks offered a potential application for co-operative techniques. As a result several papers were produced (Shuttleworth, 1988; Smyth, 1987, 1988) which investigated how designers go about generating solutions. In general, it was reported that designers are solution focused, that is, they pose tentative solutions to a problem and by so doing learn about the problem. Through this iterative process of analysis, synthesis and evaluation, the design focuses toward a satisfactory solution.

As the work progressed it became clear that the early aims of producing general co-operative techniques were impractical. There was a pressing need for an easily understood task that was familiar to the author and which could act as a vehicle by which to articulate the concepts underpinning co-operative behaviour. As discussed in the previous chapter, the problem domain selected was room layout design, which is a sub-class of spatial design problems.

As a preliminary to the identification of such a task domain a series of requirements were identified:

- the task should be recognised as 'real world' in nature;
- there should exist a variety of possible solutions within a finite set, so as to provide the possibility of the production of alternatives between the co-operative parties;
- task goals should be identifiable and expressible at the outset of co-operation;
- explicit rules should be involved in the production of solutions;
- the task should support the generation of partial solutions;
- the task should support graphic based interaction.

The importance of this decision should not be understated as it provided an achievable focus for discussion and the eventual implementation of the co-operative machine prototype. At this juncture it should be stated that the eventual software prototype was never viewed as a room layout application, as many more sophisticated solutions already existed. The prototype aimed to use the application area as a medium by which to express the three underlying mechanisms of co-operative behaviour and, as such, room design acted as a task metaphor for co-operation between humans and computers.

3.5.1 The Design Process - A Vehicle for Co-operative Problem Solving

In design it is common that high level goals are expressed in terms of constraints and requirements (Gross et al, 1988). Designers of all varieties work within constraints and requirements; those as a result of the medium in which they choose to work, those caused by client or user requirements and finally those as a result of the task. Rather than restricting the process of design, Laurel (1986) states that, 'constraints provide the security net that enables people to make imaginative leaps'. The potential advantages of co-operative behaviour within the design process has been indicated by several researchers. Broadbent (1973) concluded that, 'in creative thinking, face to face group members may 'spark off' ideas against each other by an assembly effect so that, finally the quality of ideas is higher than the individual could have achieved'. While Middleton (1967) observed that hypotheses testing is an area which benefited from group activity when he stated, 'the distinction between original thought, which is a lonely activity, and the testing of hypotheses, a logical process where the group can participate with advantage'.

The next question was are there general rules within design, and in particular spatial layout, which could be incorporated within the partner model? Such rules would form the mechanism whereby the co-operative machine could generate meaningful alternative solutions, a factor vital to achieving synergy within the co-operative dyad of human and computer.

Designers are often confronted with the task of choosing, from among an apparently limitless number of possible arrangements, an aesthetically satisfying composition of objects within a given space. Some choose to rely on the intuitive application of their skills. Tufte (1983) points out, in reference to graphic design, 'there are no compositional principles on how to create that one graphic in a million'. Nor are there any in other fields of design. Nonetheless, some designers cut down the number of possibilities in compositional tasks by applying rules to govern the placement of objects in a few initial sketches. They can then choose to enforce the rules more or less strictly, apply further rules and develop compound effects, in response to the resulting compositions. A fundamental compositional solution is to arrange objects along lines of symmetry. Another rule that has been applied for centuries is that of the Golden Section (Holt, 1971). Rules of this nature were considered as essential to the partner model if it were to successfully co-operate with the designer, and, as the role of the prototype was paradigmatic and called for only a few archetypal rules to illustrate the principle, it was not considered appropriate to research the area exhaustively.

By the adoption of the room layout metaphor, it was considered that the requirements of the agreed definition knowledge base could be met by the inclusion of a subset of generic furniture objects which could then be acted on by both goal definitions and rules within the partner model (i.e. desk, filing cabinet etc).

3.6 The Initial Co-operative Prototype (P0)

At the outset of the implementation of the co-operative prototype two system design decisions were made, these were as follows:

- to, when possible, place control of the interaction in the hands of the user.

This refers specifically to junctures during the interaction which require judgements to be made, for example, a decision as to what object configuration constitutes a satisfactory layout solution.

- to minimise the requirement for explicit broad band communication between the user and the machine, and to instead adopt an implicit, graphically based, communication technique.

The rationale behind this description was that because designers work in primarily visual environment it would be important to reflect this in the interaction style of the prototype system.

The prototype P0 was implemented in C-Prolog mounted on a Hewlett Packard workstation and used a general purpose environment built at the LUTCHI Research Centre at Loughborough University (Murray and McDaid, 1993).

3.6.1 The Interface

The philosophy adopted with respect to the prototype interface was an emphasis on visual representation of task information. Informal observation of two human designers co-operating during a shared task indicated the requirement for two dedicated graphical windows, which represented a view of the floorplan of both the user and the partner respectively (see Figure 3.3). This was a simple solution that overcame the problem of presenting alternative solutions to the user, while not causing a distraction from the current task. Other user actions, such as the construction of goal, the prioritisation of the partner model rule base and the creation of objects, were achieved through selection of appropriate software buttons. Figure 3.3 presents an annotated screen shot of the interface of prototype P0.

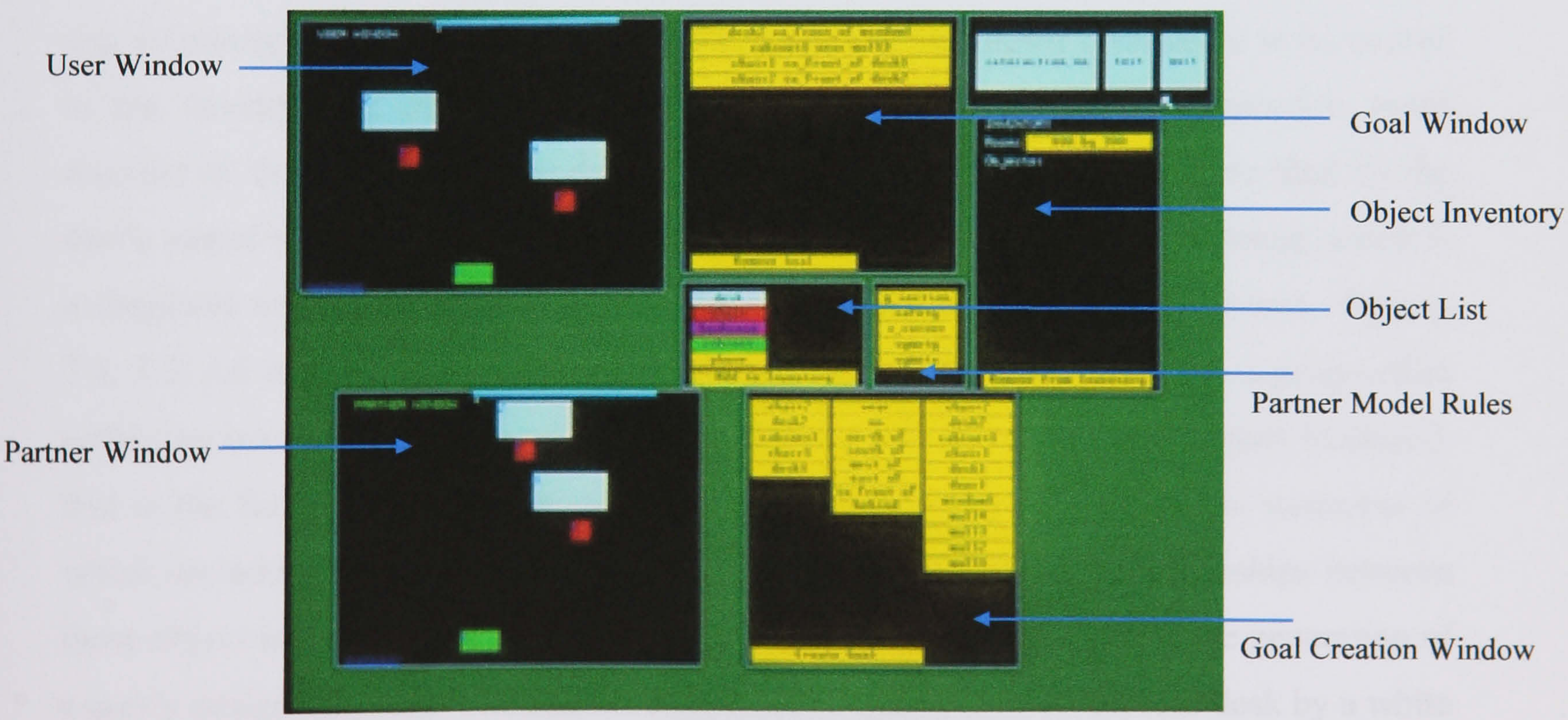


Figure 3.3 An Annotated Screen Shot of Prototype P0

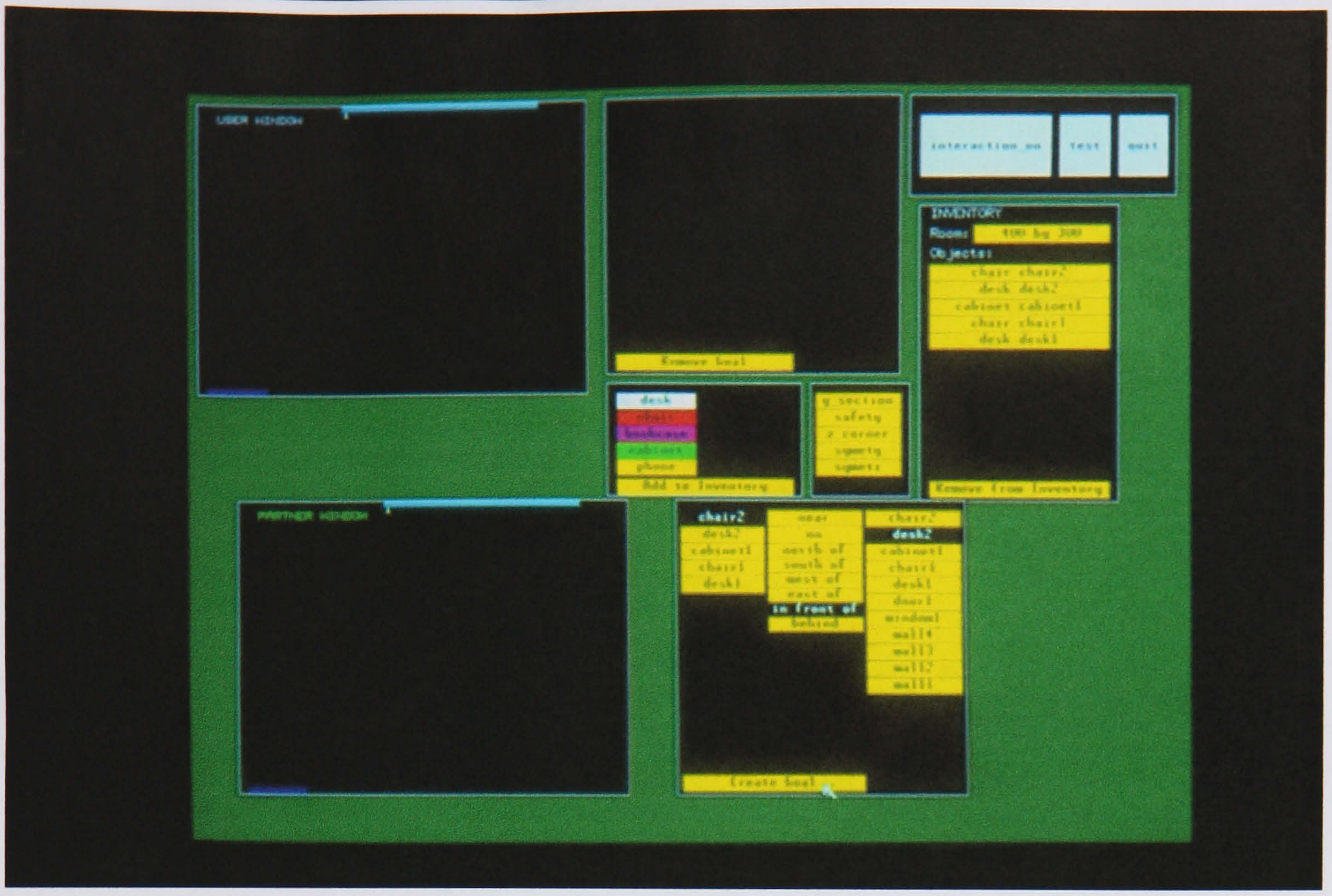


Figure 3.4 Selection of Objects and setting Spatial Relationships between them (Goals)

The prototype has two modes of operation: solve and interactive. When the solve mode is activated the partner model will immediately generate an alternative solution based on the current active goals and the location of objects in the user's solution. The solve model was primarily used during software development and was never considered to be central to the development of the co-operative relationship. Whereas the interactive mode resulted in the situation where the activation of the partner model is controlled by the user's selection of object locations, a method which was thought to characterise, albeit at a simplistic level, the equivalent relationship within human-human co-operation. Figures 3.4, 3.5, 3.6 and 3.7 show screen shots from prototype P0 which illustrate a progression within an interactive session. Figure 3.4 presents both the selection of object instances, that is the furniture with which the designer wishes to populate the room, instances of which are added to the object inventory, and the setting of spatial relationships between those object instances (e.g. chair2 in_front_of desk2). Figure 3.5 shows the generation of a user's design solution. The furniture objects are represented as follows: desk by a white

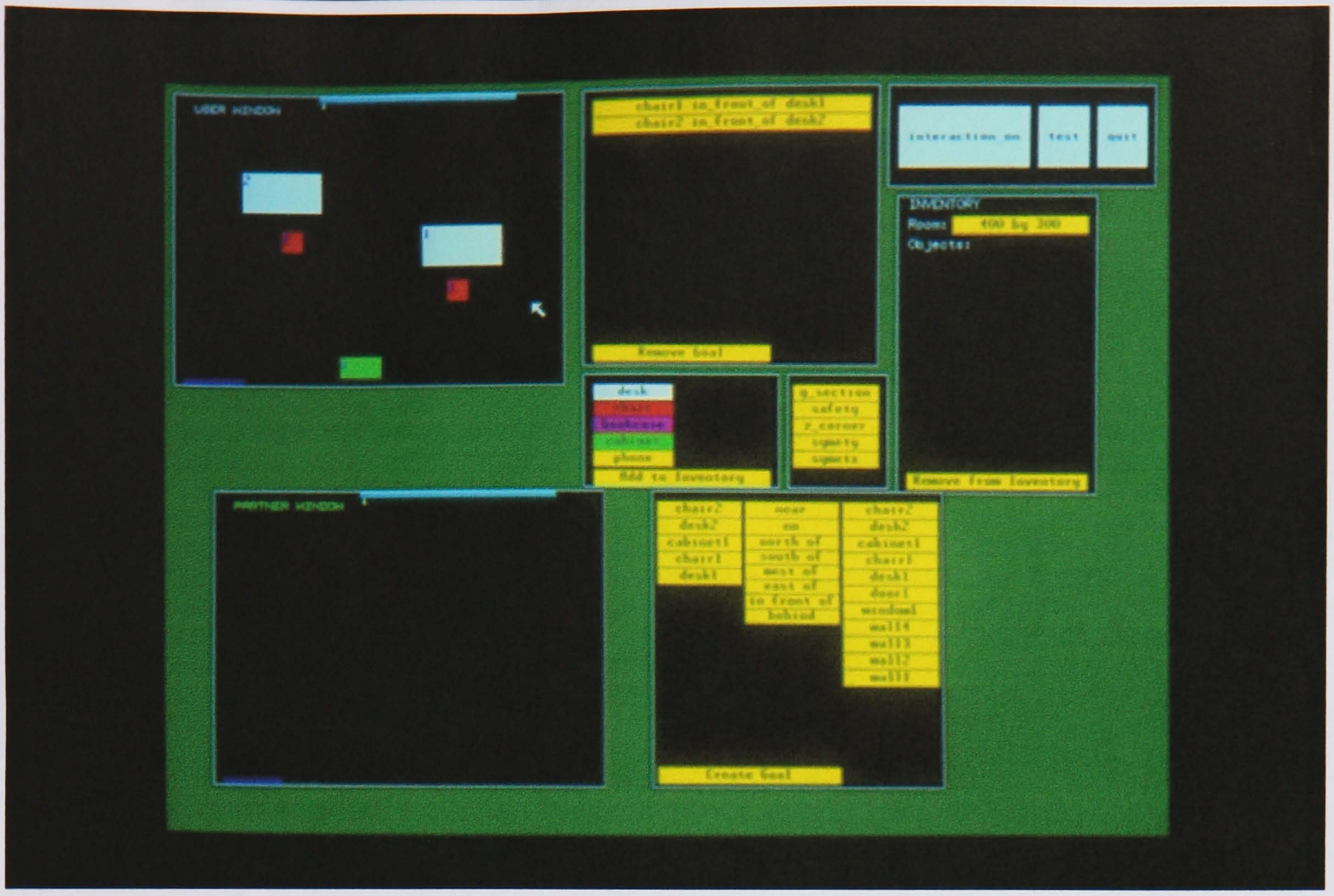


Figure 3.5 Generation of User's Design Solution

rectangle; chair by a red square; bookcase by a purple rectangle; filing cabinet by a green rectangle and a telephone by a yellow square.

Certain fixed elements were present within the room. A window located on the north wall was represented as a light blue strip and a door on the south wall of the office was represented as a dark blue strip. Figure 3.6 presents the alternative solution generated by P0, which is presented in the partner window. This will be based on the current design of the user, the priority of the Partner Model rule base and the goals as set by the user. Finally, Figure 3.7 illustrates the effect of the user forcing the Partner Model to use the particular placement of an object, which in this case is the green filing cabinet.

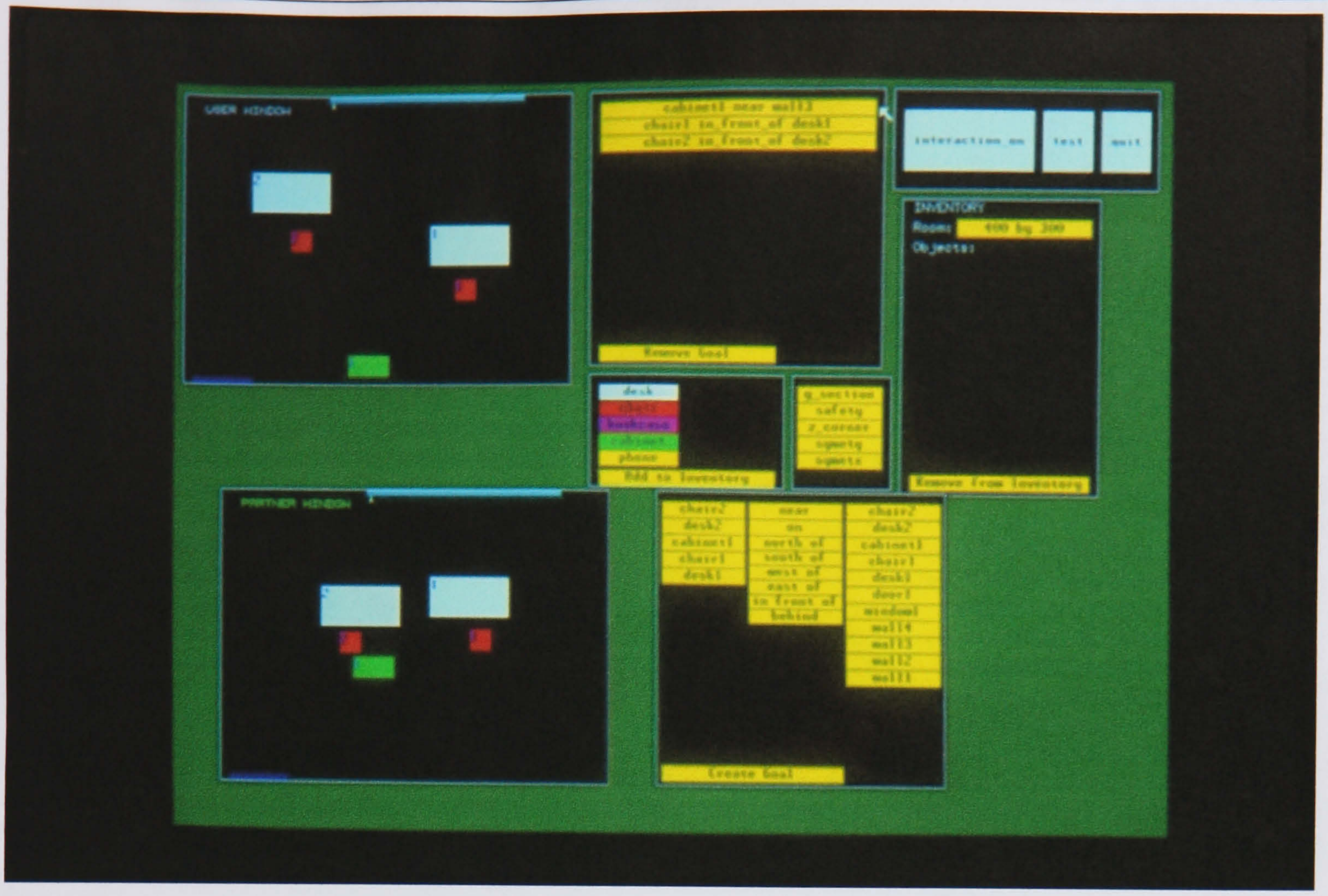


Figure 3.6 Generation of Alternative Solution by P0.

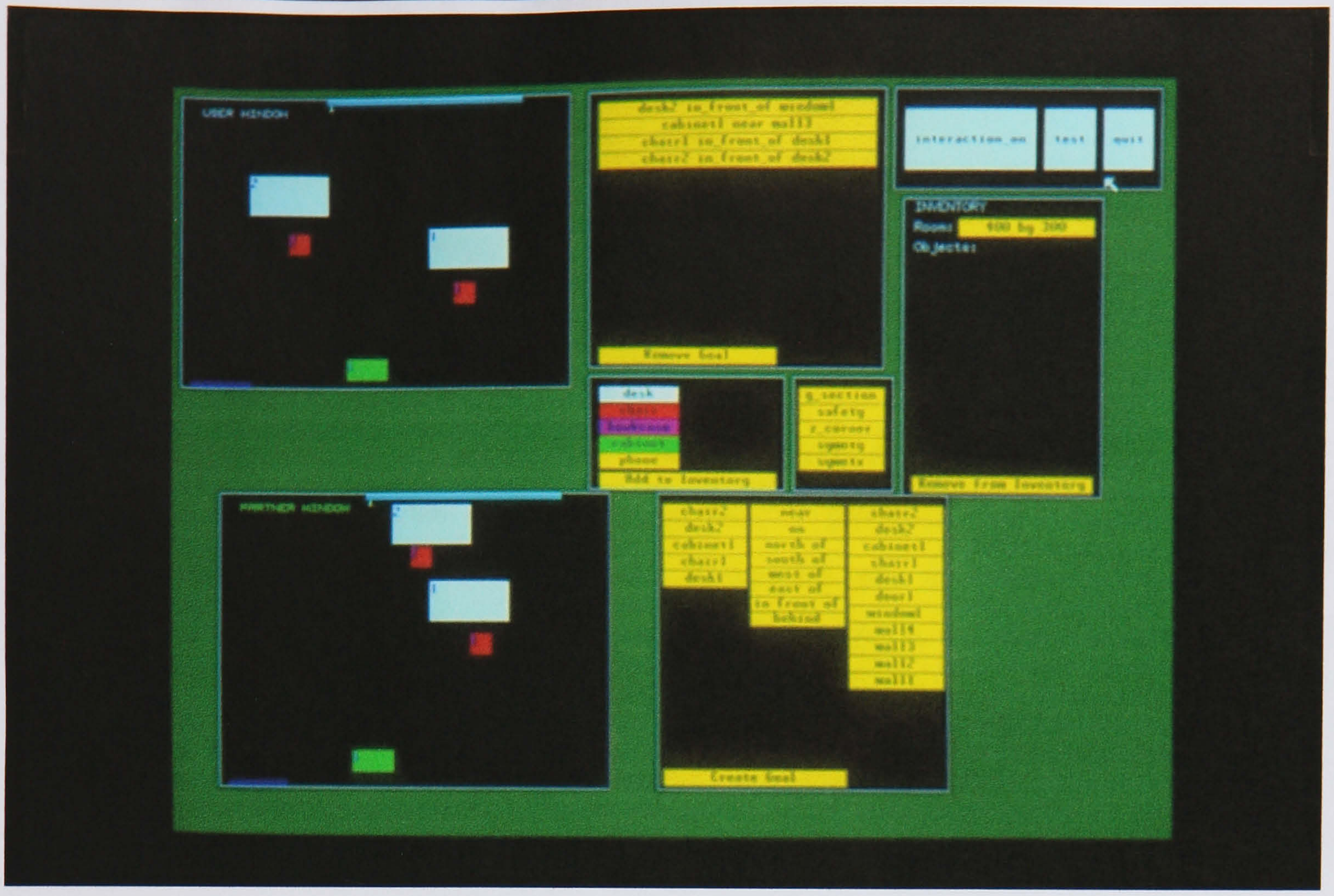


Figure 3.7 User forcing the Prototype to conform to their placement of a specified object (the green filing cabinet).

3.6.2 The Agreed Definition Knowledge Base

The room design metaphor contained a deliberately constrained, hand crafted, object set which was presented visually to the user throughout the interaction. Selection of an object type caused the creation of an instance of that object to be placed in the inventory. The user was then at liberty to incorporate that object instance within a goal construct or simply place a graphic of the object in the user window at the desired location. Both the user and partner windows represent a notional floorplan. As objects are located in the user window the partner model generates alternative positions based on its rules and displays its option in the partner window. Throughout this process parallel agreed definition knowledge bases are being continually updated as the user and partner generate alternatives of the available objects. The standard object data structure is as follows:

object (< user / partner >,

object_type (object_instance),

location,

< permanent / moveable >).

Transfer of data from the databases was at the discretion of the user, who had the ability to either freeze objects in the user's window, thereby disabling the effect of the partner model, or transfer object configurations generated by the partner model to be incorporated within the user solution. It was felt that both these techniques have similarities to those observed in human-human co-operative behaviour.

3.6.3 Goal Oriented Working

A software technique developed within LUTCHI (Murray and McDaid, 1993) provided the enabling technology for the representation of goal oriented working within the prototype. It enabled the user to construct spatial relationships between objects that were then translated into the Prolog rule base that enabled the partner model to manipulate them. The provision of a method whereby the user was able to visually construct goals was central in the development of the software prototype.

A representational number of spatial relationships were hand crafted in the system, and users were able to construct and delete goals as required during the interaction. The relationships were object sensitive. For example the concept of nearness is quantitatively different when applied to a desk wall combination than to a desk chair combination. As the user selected instances of object types, they were added to a list of fixed object instances and presented in an Inventory Window (see Figure 3.4). Object instances took the form of: wall1, wall2, desk1, and window1. This list was also displayed in another window together with a number of spatial relationships (e.g. in_front_of, near, on). The user could then construct simple goal statements by selecting the appropriate items from the three column list, which the prototype would seek to accommodate within its alternative solutions. The goal statements were in the following form:

<object_instance> <spatial_relationship> <object_instance1>

The goal oriented working mechanism also included simple conflict checking which alerted the user to possible sources of goal conflict. Once the goal list has been created the software calculates the order in which to place the objects. If, for example, the following goals were created,

phone	on	desk
desk	near	wall

the desk would have to be positioned first before the initial goal could be satisfied. If goal fulfilment was deemed to be object independent the order of creation was the deciding factor. Examples of user constructed goals are as follows:

cabinet1	near	wall2
bookcase1	near	wall3
bookcase1	near	wall4
desk1	near	window1
chair1	in_front_of	desk1
chair2	in_front_of	desk2

3.6.4 The Partner Model

The partner model consists of a subset of design knowledge concerned with the proportionality of objects within a finite space, in this case the location of furniture within a room. Examples of the rules in the partner model include; symmetry, golden section and safety, the latter being chosen as it reflected a different style of rule. The safety rule caused an access route between the window and door to always be clear. At each stage in the user's development of a solution, the partner model can interrogate the resulting object configuration and apply its rules thereby generating, within a number of user defined goals, an alternative composition of the objects based on the user's solution. The design solution generated by the partner model is neither right nor wrong, but is a viable, alternative configuration of the user's objects developed using a different rule set to that of the user and its aim is to act as a spur to the user's imagination. Incorporated within the partner model's solution strategy is a mechanism for the identification and rejection of alternative solutions that break fundamental constraints implicit in the task domain. For example, objects must remain within the bounds of the room and must not occupy the same space.

The facility to alter the order in which the partner model rules were applied was available to the user. This enabled the user to view a number of alternative object configurations each generated by a partner model with a different emphasis or style. Division of labour was thus placed in the hands of the user so, for instance, the user could indicate that he wished the partner model to place a high priority on safety, so leaving himself free to pay more attention to the stylistic details of the solution.

3.6.5 Role of the Software in the Development Cycle

The development of the prototype was of great benefit to the research as it provided a tangible demonstration which led to many fruitful discussions and ideas which could later be incorporated in the software. At this stage in the development process an informal evaluation of the prototype system was undertaken. The nature of the prototype suggested that a co-operative approach to the evaluation process would be appropriate. Co-operative evaluation (Preece, 1994) suggests that the evaluator sits with the user while they interact with the system under study. At the outset the user is instructed to 'talk aloud' in order to verbalise their behaviour. At any stage the user and evaluator can engage in a dialogue in order to, for example, clarify a point during the interaction. The approach is extremely flexible and well suited to prototypes that have a natural tendency toward instability, of which the co-operative machine was a good example.

Two final year students from the Department of Design and Technology at Loughborough University agreed to participate in the evaluation that took place over an afternoon. A number of points were raised during this process:

- both designers stated that they enjoyed using the system, although they acknowledged that they had never used such a system before in the context of design;
- there was a general concern about the simplicity of the alternatives produced by the system. While initially the approach was interesting, it soon became relatively easy to predict the location of certain elements in the alternative solutions;
- the concept of rule manipulation and its consequent impact on a design solution was a relationship about which both designers were positive. They enjoyed the experience of exploring solutions by means of manipulating goals and object relationships.

Although at a rudimentary stage in development, the experiences gained during the process only served to confirm the belief in the potential of co-operative computing.

3.7 Conclusions

The primary objectives of the work described in this chapter were as follows:

- the identification of the mechanisms central to the development of co-operative machines;
- the exemplification of these mechanisms in software.

As a result of the design, development and evaluation cycle presented in this chapter a number of conclusions have been made:

- end user manipulation of the data shared with the partner is an enabling technique which is central to the development of co-operative machines;
- in order to have the potential to produce alternative solutions the partner model rule base must remain autonomous from the user if the co-operative machine is to avoid the pitfall of simply mimicking the solutions generated by that user.

3.8 Discussion

3.8.1 Software Development

The degree of co-operation achieved by the machine will be as a result of interaction between the underlying mechanisms, not as a result of their individual action. How this resulting machine behaviour will be manifest to the user will be dependent on the interface. Within the context of the room design metaphor a number of interface requirements were identified. By adopting the philosophy of visualisation of knowledge, the interface should enable the user to firstly, define task objects and secondly, to support the interactive definition of goal relationships. In short, the interface of a co-operative machine should enable the user to enhance the agreed definition knowledge base and thereby more directly focus the process of generating alternative solutions and so increasing the degree of co-operation perceived by the user.

3.8.2 The Partner Model

The requirement for a distinction between the partner model rule base and the user raises some interesting issues concerning the nature of modelling partners in single user co-operative machines. Co-operation between humans is a dynamic relationship, as it is assumed that both parties are learning/reinforcing the concepts being expressed by their partner during the interaction. Over a sufficient time period it is foreseeable that the co-operative relationship could become static, as without the introduction of new sources of information a commonality of views might become implicit between partners so reducing the effectiveness and, ultimately, the creative potential of the relationship. In human-human co-operation additional information can come for a multitude of sources and is reflected, for example, in the individual's background, education and personal preferences. On the other hand the current machine model of the co-operative partner is static. A single-user system does not provide an alternative source of information necessary for the partner model to develop during the interaction, and the use of information gleaned from the user during interaction, as in dynamic, embedded user models, would reduce the difference between partners and remove a plank felt vital to the co-operative relationship. In short, the ability of the human partner to learn during a co-operative interaction ensures a limited period of usefulness for a static partner model in a single-user system. As the user becomes cognisant of the partner model rule set, the machine generated alternatives become predictable and no longer a spur to the user's imagination. In the context of human computer co-operation a partner model is proposed as a technique to represent the essential difference between the user and the machine necessary to realise some of the dynamic qualities of co-operative problem solving.

The work undertaken during this phase of the research has highlighted several important issues felt to be central to the development of future co-operative machines, they are as follows:

- the depth of knowledge required to support co-operative working suggests that the technique is domain specific;
- what constitutes co-operation varies between tasks. The existing problem solving process adopted by human partners must be clearly identified before attempting to build a co-operative machine;
- the mechanisms of Goal Oriented Working, the Partner Model and an Agreed Definition Knowledge Base, as described in this chapter, provide an outline architecture for co-operative machines;
- it is the interaction of these software mechanisms and how the resulting behaviour is manifested to the user, via the interface, that will determine the amount of machine co-operation perceived by the user.

The issue of developing a system that has the potential to continually surprise and inspire the user is, indeed, a challenge. It was primarily this issue that seriously curtailed the widespread deployment of the agent and critic based systems during the 1990s. Agents and critics have sought a solution to this problem through a 'community' based approach, exemplified in the Recommender Systems which glean information based on the suggestions of multiple users or organisations and use this as a basis from which to proffer advice to the individual user. In a similar manner, critics have been integrated into DODEs which seek to harness the potential of multiple users and hence what Fischer (1999) refers to as 'social creativity'.

Somewhat against this prevailing trend towards the social, the prototypes P1 and P2 that will be discussed in the remainder of the thesis have adopted a grammar based approach to the representation of knowledge. Such an approach, it is contended, offers the potential to generate an infinite number of alternatives from a finite set of rules. Before addressing this issue it is appropriate that the task domain of design be studied in more detail, and it is this phase of the research that will be reported in Chapters 4 and 5.

3.9 Epilogue for Prototype P0

The evaluation of prototype P0 marked the beginning of a change of emphasis within the research. In retrospect, the point where this change began was during the feedback provided by the designers as they interacted with the prototype. Specifically, that their interpretation of the prototype's behaviour was from the perspective of the discipline of design. On reflection, this should have come as little surprise, but the reality was that it did. Up until that point the prototype had used the domain of design as a vehicle with which to articulate particular aspects of co-operation and how they would be manifested within technologies. The artificial nature of the distinction between the software design approach (i.e. co-operation) and the means through which it was expressed (i.e. design) was made apparent during the evaluation of P0. As a consequence the focus of the research began the process of transformation into a study of the early phase of design and, ultimately, so did the aim of the work to the investigation of computer based support of this activity.

4 Design and its Support by Computer based Tools

4.1 Overview

This chapter with present the following themes:

- an overview of the activity of design, in particular the role of drawing;
- a summary of technology support of the early phase of design;
- an interpretation of design from the context of co-operation.

4.2 Introduction

As an initial step towards the development of technologies to support the early phase of design, an overview of the literature was produced and is presented in this chapter. The focus of the literature study is the role of drawing within design, as it is contended that design sketches are the primary means through which designers articulate their early design ideas. Furthermore, it is the view of the author that the earliest point where technology can contribute to the design process is when the designer has produced a tangible expression of an idea (i.e. a conceptual sketch). To conclude the literature study, a number of representative computer based systems are described. These systems exemplify a number of approaches to the support of the design process and serve to orientate the reader as to the emphasis, if not the nature, of the later prototypes reported in the thesis.

4.3 An Introduction to Design

Design is about finding solutions to problems. Whether it's the construction of a building within a given brown field site and in keeping with the existing structures, or the generation of an office floor plan to accommodate a specified number of staff in both safety and comfort. Designers are solution focused, that is, they seek to generate and discover constraints through the generation and analysis of solutions (Lawson, 1997). Design problems are, on the other hand, 'ill-defined' (Simon, 1973) or 'wicked' (Rittel and Webber, 1972). They do not have an optimal solution and the problem cannot be precisely specified before attempting a solution (Fischer et al, 1991). The analysis of why certain solutions perform better than others is an integral part of the design process. Successful design relies on critical analysis early and often in the lifetime of the activity.

Central to this process is idea articulation and, as shall be reported in Chapter 5, traditional design tools, such as sketches, physical models and Computer Aided Design (CAD), enable this in particular ways. Furthermore, the ensuing dialogue that occurs in conjunction with idea articulation, either with the self or with others is, it will be argued, as important as the process of generation itself. This position is supported by the work of Cross (1996), whose study of a group trying to design a device for carrying a hiker's backpack on a mountain bike, reported the impact of a single phrase, in this case 'tray', and how it influenced the remainder of the design process. Cross interprets this as language forming a 'bridge' between problems and solutions, rather than a 'leap' which could be the conclusion if only drawings were analysed. As a position from which to begin the consideration of the early phase of design the next section will consider the role of sketches.

4.4 The Role of Sketching in Design

The act of sketching provides a designer with perhaps their most flexible technique for concept exploration. Critically, sketching enables the designer to adopt a representational medium which, it is suggested, will help to formalise abstract thoughts (Broadbent, 1973). The act of making marks on paper represents a key point in the design cycle, as it is the earliest stage where computational support might begin to impact on the activity of design. Indeed, Willey (1976) suggests that sketching provides two major benefits, firstly as technique for the synthesis of ideas through externalisation and secondly, through the provision of visual cues as a means of manipulating complex relationships. Sketching enables communication both with others but also critically with the designer themselves.

In the context of communication with others Cuff (1991) comments on the role of sketches and in particular the form that they take during the initial phase of the relationship between an architect and a client. She contends that a graphic dialogue between the architect and client begins in earnest during early meetings, where the architect employs what Cuff refers to as 'loose' sketches to expose tentative visual ideas to the client. One architect is reported as explaining the advantage of a scribbled sketch as a 'move from words to images, beginning with images that are non-specific'. By keeping sketches (or early models) murky, architects hope to raise issues or confirm impressions that will later inform the building design. The non-specific nature of these early sketches raises an interesting issue concerning the conceptual level of domain representation that a computer based tool should utilise if it is to support the early phase of design. This point, coupled with the criticism of prototype P0 (i.e. that its solutions were seen as overly simplistic due to the inappropriately high level of expectation of the designers), suggests that such a tool would benefit from adopting a more abstract approach to the representation of design objects.

At the level of the individual designer, the act of drawing plays a central role in the articulation of ideas during the design process. The production of sketches provides a means of active engagement with the problem through which designers can learn about the concepts and relationships in the problem domain. This perspective is similar to that proposed by Papert (1980) when he suggested an active environment as a tool to enable creative learning about a problem domain in which users could generate and test hypothesis as a means of learning. Within design, experimentation can take place in the form of attempts to abstract patterns of user requirements, which may eventually be manifested as concrete patterns of an actual object. Design sketches act as a tool for thought. They have the potential to foster an expression of thought necessary for design creativity, but that is not to say that using sketches will result in a creative design, simply that they are one of a number of tools available to the designer that enable idea articulation. An important feature of sketches is that they include tolerances and indeterminancies that can enhance the drawer's ability to perceive or imagine options. Leonardo da Vinci first described and advocated the deliberate use of 'untidy indeterminacies' to stimulate invention by pointing out that 'confused things rouse the mind to new inventions'. Leonardo used his sketches as he used the marks on crumbling walls to help his inventiveness regardless of the subject (Fish and Scrivener, 1987). In a similar manner, while attempting to characterise the level of engagement with a problem offered by sketches, Schön (1983) referred to this as the designer having 'a conversation with the situation' through the medium of the sketch.

But the power of drawing also hides some potential pitfalls. Drawings are beguiling and designers must take care not to 'design the drawing, rather than the object that it represents' (Lawson, 1997). He also raises the interesting question of whether the drawing tool mediates the cognitive phase of the designer. McLuhan (1994) stated that the 'medium is the message' but for designers it might be that the 'medium is the frame of mind'. That is, the medium chosen to consider a problem is indicative of the individuals current thinking about that problem. This emphasises the intimate nature of the relationship between designers and the tools that they use to design. A point which designers of technologies to support design ignore at their peril and an issue that will be considered in more detail in the next chapter.

4.5 A Sociological Perspective of Drawing

Robbins (1994), in his book entitled 'Why Architects Draw' adopted a sociological standpoint from which to consider the role of drawing during design. Drawings, he contends, are introduced as a means of clarification, primarily with a client where they are characterised as directing, ordering, clarifying and recording ideas which are expressed verbally. In a similar position to the author, Robbins suggests that drawings can encourage architects to enter into conversations with themselves as a method of better understanding the problem at hand. Furthermore, that drawings are pivotal in imposing order and structure on the social interaction and relationships of the actors who participate in the activity of creating a building. In short, those drawings provide an important instrument through which the social production of architecture is organised.

4.6 Drawing as a Language of Design?

Drawing serves as a primary medium for generating, testing and recording the individual designer's own creative and conceptual thoughts about design. It also serves as an instrument of communication. But does that mean that drawing acts like a language of design? Kolb (1990) argues that architecture is not a language *per se*. He states that 'buildings do not combine their parts to make predictive or relational assertions'. Rather, he asserts, architecture acts like a language. Its parts combine, recombine and substitute for each other with different resulting implications and potential meanings. Whereas Graves (1977) asserts that drawing is used by architects in their own thinking and design processes as an internal conversation and as a way to record, test and reflect upon design. Whether all architects would agree with such a characterisation is an open question. For some the very act of drawing - the action of hand on paper - is the basis for their ideas. In a study of design practitioners (Lawson, 1994) quotes the architect Michael Wilford as speaking about the value of 'the immediate process of drawing lines on pages'. According to Schön's theory (1983), designers work in an alternative cycle of action and reflection. A designer acts to shape the design situation by creating or modifying design representations, and the situation 'talks back' to the designer, revealing unanticipated consequences of the design action. Understanding the situation's 'back talk' requires skills of designers, who need to reflect on actions, interpret consequences and plan the next course of action.

While such variation perhaps reflects the range of cultural practices that drawing enables within design, it is also fair to claim that there is a consensus among practitioners that drawing is perhaps the crucial instrument of design discourse. Indeed, many would argue that until one delineates the design concept in a drawing then one really couldn't claim to understand it in the first place.

Schön (1992) argues that designers are in 'transaction' with a design situation, that is they respond to demands and possibilities of a design situation, which, in turn, they help to create. These creations are referred to as 'design worlds' that can be individual to the designer or shared with others. He goes on to comment that a designer's 'knowing in action' involves sensory and bodily knowing. Schön presents the designer as a constructor and explorer of 'design worlds' with which they interact in both a cognitive and physical sense. This position is reminiscent of the phenomenologist Merleau-Ponty's (1962) account of 'being-in-the-world' and the importance of the body. This position has been developed, for example by Dreyfus (1996), to explain skill acquisition. Merleau-Ponty places the body at the centre of our relation to the world and argues that it is only through having bodies that we can truly experience space. Not surprisingly a number of ideas underpinning phenomenology have been appropriated by the design community when discussing the acquisition of design skills. This in turn has led some researchers (e.g. Tweed, 1998) to comment that design based skills are bodily as much as cognitive skills. The issue of the role of the body, and the part it plays in how we make sense of and interact with the physical spaces that we design and inhabit and which constitute our environment, will be returned to later in the thesis in relation to the haptic qualities of design tools and how such attributes might be introduced into computer based tools.

The traditional tools of hand sketching and physical modelling are intimately bound to the activity of design. At the pragmatic, cultural and social levels their usage exerts both explicit and implicit influences on how design is undertaken and the results that it achieves. This raises the question of how might technological tools be designed to both complement and enhance such a complex relationship? The next section will present a rationale with which to consider the relationship between design and technology and will conclude with a summary of some representative computer based design tools, with the purpose of placing in context prototype P0 and framing the prototypes P1 and P2.

4.7 Computers and Design

Today much of mainstream CAD technology addresses the needs of draughting rather than design (Tovey, 1989, Frazer and Rastogi, 1998). It provides increasingly sophisticated ways of presenting design ideas rather than aiding with the production of those ideas in the first instance. In reality CAD stands for Computer Aided Drafting rather than Design. A notable exception to this generalisation is the work at Xerox, reported by Carter (1993). This approach sought to enhance tradition media with computational tools and emphasised the importance of the physical workspace and how paper was distributed in this space. It proposed a digital drawing board, based on the work of Wellner (1991) which sought to integrate physical and computational media. This research criticised CAD systems due to their lack of physicality, which is an issue that will re-emerge during the course of this thesis. Even in the face of technological progress true CAD remains something of a mirage, raising the question why has technology failed to make a significant impact on design, when compared with other disciplines?

To assist in answering this question, the role of technology in relation to the design process will be considered together with a number of systems, which are pertinent to the work described within the thesis. Solely for the purpose of discussing the areas of design that have been the focus of technological support one can adopt the broad classification of analysis, synthesis and evaluation. Support during the analysis concerns the articulation of the problem. While evaluation deals with tools which effectively critique a design solution along some pre-defined criteria. The synthesis phase of the design cycle is the area that provides the focus for a summary of some representative systems, in particular, those systems with an emphasis on solution generation within a design environment. The purpose of this is not to provide a complete summary of existing systems but is to frame the problem that will be the focus of the remainder of the thesis. Before such an exercise it is necessary to provide a framework from which to both interpret and relate these systems.

4.8 A Taxonomy of CAD Tools

CAD systems have in general ignored the progression from abstract concepts produced early in the design cycle to more detailed drawings and models. CAD tools support only the later phases of designing and as a consequence they require the designer to identify design elements and relationships specifically and precisely, rather than at the abstract level more typical of the early conceptual phase. As a consequence many designers continue to use traditional tools and only use CAD systems for the representation and presentation of design ideas. It is only at this stage that the design can be specified at a level of detail appropriate to the CAD system. Perhaps this is an instance of a more general problem associated with technological assistance during tasks, that before technology can assist with a problem, that problem must be expressed at a level of detail which requires the problem to be all but solved in the first place. Furthermore, this supports the growing contention that a more abstract based dialogue would be appropriate for systems aiming to support the early phase of design.

This raises some interesting issues with respect to the input and output of systems designed to support the early phases of design, irrespective of how that support is achieved. Input can be in the form of either sketches produced by the designer which have to be interpreted by the system, or via a combination of objects known to the system which the designer has manipulated into a desired combination. Output, on the other hand, can be considered as an evaluation of the designer's original solution. For example, pointing out shortcomings in the original, or critiquing the solution from the standpoint of statutory regulations pertaining to the building type. Output can also be of a generative nature, that is, the system uses the original design as a basis from which to generate alternative solutions. In summary, such systems can enable input via the manipulation of objects known to the system or through free form design input that has to be interpreted by the system. While in terms of output, such systems can evaluate the designer's solution or can generate new solutions based on the original input.

4.8.1 Manipulation

This approach places more constraints on the designer through the provision of a set of objects which are known by the system and which can be configured in a variety of ways and in accordance with rules associated with the object behaviour. The advantage of this approach is that the technology can reliably interpret the design input. This technique was used by the prototype P0. The designer was presented with a fixed set of object types with which to populate an office floor plan. The designer could select as many instances of each type that they desired but could not generate new object types. This made the task of interpreting the designer's solutions easier in terms of computation.

4.8.2 Interpretation

This approach to input places the minimum number of constraints on the designer's sketches which have to be produced in a machine-readable form, using for example, a graphics tablet and a pen. In such a scenario the emphasis is placed on the technology to interpret such sketches as a necessary precursor to its involvement in the design process.

4.8.3 Evaluation

Once the input provided by the designer has been transferred to the computer, and irrespective of what transformations take place therein, the results must be output to the designer. This usually takes the form of a critique of the original design. See for example the work of Fischer's Group at the University of Colorado (see Section 2.15.5).

4.8.4 Generation

A second output strategy is that of generation, where the technology attempts to generate alternative solutions based on the input provided by the designer. For example, by attempting to reflect the location and spatial relationships of particular objects based on those of the original design.

What follows is a summary of several technological systems that are considered pertinent to the approach adopted within the thesis. The intention is not to provide a complete summary of technology and the support of design; rather the aim is to frame the problem for the reader. Furthermore, it is acknowledged that the characterisation of Input and Output may not be as exclusive as represented in the matrix.

	Evaluation	Generation
Manipulation	Janus, Spaces	Baid, W&E, Stuni, Frazer, Prototype P0
Interpretation	Cocktail Napkin	

Figure 4.1. The Input-Output Matrix populated with the Systems described in the next section.

Figure 4.1 presents an Input/Output matrix populated with the systems described in the next section. Interestingly, the Interpretation-Generation quadrant remains empty and is indicative of the complexity of such an approach. The majority of the systems described fall into the Manipulation-Generation quadrant and this reflects the approach that will be adopted by the research reported in the thesis.

4.9 A Review of Pertinent Computer Aided Design Systems

Using the distinction between systems that support the analysis phase of design and those which support the evaluation of solutions, as outlined earlier in the chapter, this section will introduce a number of computer based systems which have aimed to support the early phase of design.

4.9.1 The Analysis Role

4.9.1.1 BAID

A system designed to help architects lay out housing developments in such a way as to satisfy the legislative constraints dealing with privacy and with daylight and sunlight requirements (Auger, 1972). The intention was that the system would generate alternative solutions and allow the designer to select, combine and modify parts of these solutions. Each of the layouts generated was different due to the initial use of random positioning of objects, which were then checked against some set criteria. Consequently, the location of objects was dependent on the current configuration of the solution and a random factor generated by the system. Anger characterised the function of BAID as follows: 'the object of producing the random generated layouts is to stimulate the designer's imagination, give him a sense of scale for the site and provide him with possible ideas for groupings etc'. The key factor illustrated by BAID was the attempt to generate alternative solutions that the designer could then choose to integrate into a solution where they considered appropriate.

4.9.1.2 Whitehead and Elder's Program

The system generated room layouts based on the minimisation of circulation distances (1964). Circulation was based on the predicted number of journeys between identifiable locations by given categories of staff over a unit period of time. Even salaries were factored into the calculation. The underlying goal of the system was to generate a solution that minimised 'circulation cost'. The designers of the system demonstrated its capability by using the design of a hospital as an example. The initial step was to identify the room with the highest level of interaction with all the other rooms and to place it at the centre of a planning grid. Secondly, to identify the room with the next highest level of interaction with the initial room and then to place it adjacent to the first. A third room was then placed using a similar strategy. Subsequent room placings are trailed and related costs are calculated, ending with the least cost position being selected.

The system received a number of criticisms, initially by Cross (1977) when he claimed that the layouts generated by the software could be bettered by some humans. Further criticisms were that in reality the input data required by the system would, by its nature, always be imprecise. For example, the practice of selecting different routes between given locations depends on the time of day. Perhaps the most profound criticism of this system concerned the wider implications of integrating technology into the design process. It raised the spectre of the computer presenting the designer with several outputs based on different criteria (i.e. lighting, circulation and safety requirements). The designer would then have to resolve these and combine them into a single solution.

While this is a possible scenario, it is not a strategy that has been observed among designers (Lawson, 1997). Interestingly, Lawson goes on to raise the question of whether it might be necessary to re-cast the design process in order to take advantage of technology. This rather worryingly echoes the past failures of the software industry when, all too often, attempts were made to fit the problem to the solution. One thing that is certain is that the deployment of CAD will not succeed through the redefinition of the design process. The contribution of Whitehead and Elder's system was to exemplify the concept of rule manipulation as a technique for generating design solutions. The coupling between rule manipulation and design generation is considered to be a critical element in the support of the early phase of design.

4.9.1.3 STUNI

Similar to the system developed by Whitehead and Elder, this system was used to design the layout of the new Stirling University campus in Scotland (Willoughby et al, 1970). This was achieved by first dividing the site into a grid where each unit was assigned a desirability factor (e.g. aspect, soil type). Buildings within the campus were then positioned in a similar manner to Whitehead and Elder's system. This system demonstrated a number of important advantages over the previous solution. Firstly, it coped with greater complexity; secondly, it could produce multi-story solutions and critically it allowed for interaction between the designer and the application by enabling the positioning of the first 'activity unit' and subsequent units. STUNI utilised a strategy of 'seeding' the generated solution by providing the facility for positioning the initial object in the plan that will then influence the positioning of the further elements.

4.9.1.4 FIXER

An interactive expert system with detail about fixtures in buildings (Fawcett, 1986). This system did not attempt to generate finished solutions automatically, a failure exhibited by many other expert systems. Rather it used its rule base to offer the designer a choice of viable alternatives at each stage during the generation of a design specification. The key aspect of FIXER is the generation of alternative solutions through the representation of design knowledge in the form of rules.

4.9.1.5 The Work of John Frazer

Frazer (1995) has worked on the idea of a set of ideas that involved computers generating families of solutions from a set of rules. For example, using simple transformation techniques such as rotation and reflection. A limited form is provided as a 'conceptual seed', which is then 'cultivated' by these transformations. These instantiations are then presented to the designer in a form that resembles an idea source book. This work addressed the issue of multiple solution generation as a result of rule manipulation. An earlier system, developed by Frazer, which has subtly influenced the research presented here was the Walter Segal Model.

4.9.1.5.1 The Walter Segal Model

A system based around a timber framed building technique suitable for self-builders in a scheme promoted by Lewisham Council. The system promoted the efficient and ergonomic use of materials and was based on a standard grid pattern. Segal was keen that builders should also be designers but discovered that help was needed in order to interpret models. Frazer built an electronic version of the panel model in which various panel combinations represented different elements of the building. These were scanned and interpreted by the computer and formed the basis for the production of plan and 3D views. Furthermore, areas could be calculated, cost determined and structural frame drawings produced. As a result, people without any knowledge of architecture or computers could design a house by building a simple model. This idea will be returned to later in the course of the thesis.

4.9.1.5.2 The Groningen Experiment

This work is based on a theoretical framework for an alternative design generation process, using computer based models to compress evolutionary time and space. The result was a prototype system, entitled Interactivator (Frazer, 1995) which utilised the World Wide Web (WWW) such that visitors to the site had the opportunity to participate in the generation of the ongoing design. The next phase of the work is directed toward the construction of form within urban planning. A prototype system has been commissioned by the planning department of Groningen (Frazer and Frazer, 1998). The prototype is based on an evolutionary model and has the ability to explain transitions from past to present and to project future alternatives. In the words of Frazer and Frazer (1998) the system is 'a what-if model for generating, exploring and evaluating alternatives'.

The use of evolutionary computing techniques within CAD raises some interesting issues. Firstly does the fact that a result is unexpected really imply some sort of creativity at work? Secondly the requirement for a more detailed description of the role and nature of the 'fitness rules' used within such evolutionary systems. Finally, an issue expressed by one of the design practitioners interviewed during the course of this research when he commented 'why not apply something that you think would be useful in the first place rather than waiting for something to fall out by chance?'

4.9.2 The Solution Evaluation Role

The systems presented in this section can be characterised as design critics. Such systems operate by critiquing a solution generated by the designer, based on a predefined set of criteria. These systems are presented here primarily because they aim to encourage a dialogue with the designer concerning aspects of their solutions and, as stated earlier, this is considered to be an important aspect of design and one which is mediated by design solutions.

4.9.2.1 SPACES 1,2& 3

Developed at the Abacus Unit in the University of Strathclyde, UK and reported by Aish (1977). The figures represent different aspects of the system and equate to analysis, synthesis and design. A system that critiqued a floor plan layout for a nursery school based on criteria such as relative distance apart of units and noise levels associated with adjacent rooms. Interestingly, the system was demonstrated using a non-design expert, in this case a domain expert. The solutions generated were indistinguishable from those of design experts. In retrospect maybe this is not so surprising given the importance of domain expertise but at the time of the work the result was to raise the spectre of de-skilling in parts of the design process. This system illustrates the idea of critiquing and the associated benefits for the production of solutions.

4.9.2.2 JANUS

A design environment based on the critiquing approach that allows designers to construct residential kitchens (Fischer, McCall and Morch, 1989). The system contains two main parts, a construction kit with a set of critics and an argumentative hypertext system containing information about general principles of design. JANUS contains a critiquing component with knowledge about building codes, safety standards and functional preferences. Based on this understanding the system signals breakdowns in the current design. These are then linked to the argumentation element of JANUS for a more detailed explanation of the critique. Fischer et al (1989) cite the example of a critic pointing out that the circumference of the work triangle (i.e. the distance between sink, fridge and oven) is greater than 23 feet. Designers who are unaware of the work triangle rule do not perceive a breakdown if the rule is violated. The associated section of JANUS argumentation explains the rationale for this rule including any exceptions and the cataloguing feature illustrates some ways to satisfy the rule.

This system is perhaps closest in spirit to the prototype P0. Critically, what distinguishes the system described in the thesis is its solution generation capacity. While Janus can provide detailed critiques and in some cases examples of standard solutions, it makes no attempt to generate alternative solutions based on those of the designer. This, it will be argued, will remain an important distinction between the approaches.

The relationship between designer and computer raises interesting questions with respect to how technology might interpret the design material in order that it might usefully provide assistance. Currently the onus is on the designer to express design thoughts to a sufficient level of detail in order that the computer can undertake assistance at any level. Indeed, it might be argued that in order for CAD systems to aid the designer the design must be complete. One solution which is being explored by Gross (1996) is that of systems which interpret design sketches in order that the system can offer assistance

4.9.2.3 The Electronic Cocktail Napkin

This system (Gross, 1996, Gross and Do, 1996) aims to support the gradual transition from diagram to schematic drawing through the provision of recognition and parsing. Both the low-level recogniser for glyphs and the higher level recogniser for configurations can be trained or programmed interactively by the designer. The parsing mechanisms can also be employed to search a sketchbook or specialist databases for similar diagrams. The scheme of recognition by a series of graphical replacement rules recalls the use of shape grammars. However, the system's replacement rules are used to parse diagrams, rather than to generate them. The key factors illustrated by the Electronic Cocktail Napkin are firstly that it attempts to interpret designer input, albeit in the stylised form of diagrams and secondly that the recognition process can be interactively trained by the designer. Future versions of the system will explore co-located collaborative drawing and the idea of a design sketchbook where images can be retrieved through the production of a sketch.

4.10 Co-operation and Design

Using the terminology presented in Figure 4.1, the emphasis of the prototypes constructed during this research can be characterised as one of providing the user with a means to manipulate basic concepts as a method of generating design solutions. The ensuing dialogue that accompanies this process, with either the self or with others, is an important characteristic of design exploration. Design exploration is viewed as an activity characteristic of the early phase of the design process. It is manifest in the production, manipulation and communication with and through alternative solutions, resulting in the potential for an enhanced understanding of the design problem. This description of the design process exhibits many parallels with the description of co-operative behaviour, presented in Chapter 2. In particular, the role of alternative solutions and their function in terms of both generating and structuring communication within a group. The case is presented in the thesis that the early studies of co-operative behaviour have influenced both the author's study and interpretation of design and the form of the consequent prototype systems aimed at supporting the activity.

If a computer based tool to support design is to compliment the existing set of design tools, it is important to study how such tools are currently used during the design process. The next chapter will report on three case studies, conducted by the author, of design tool usage, specifically hand drawing, physical modelling and CAD. The aim of the studies are twofold: firstly to better inform the design of the proposed computer based tool and secondly, to ground the research in actual design practice.

5 Three Case Studies of Design Practice: Design Tools as Agents of Disclosure

5.1 Overview

This chapter will introduce the following:

- a description of the methodology adopted during the case studies;
- case study 1: a ski centre;
- case study 2: accommodation and gallery space for artists;
- case study 3: a recording studio;
- a statement of conclusions drawn from the work;
- a discussion of the conclusions and implications for the design of computer based tools to support design.

5.2 Introduction

Technological support of creative design has, to date, remained illusive (Frazer and Rastogi, 1998). While Computer Aided Design (CAD) systems have been successfully deployed in many professional practices and are incorporated into teaching programmes, their contribution has, in the main, been at the latter phase of the design cycle. This emphasis on draughting has resulted in systems which enable ever more sophisticated ways of representing design ideas, rather than tackling the issue of how technology might usefully contribute to the production of those ideas. Indeed the view that technology should contribute throughout the whole design cycle was proposed in the 1960s, most notably by Mann and Coons (1965) when they characterised the relationship between human and computer, in the context of design, as one that should be based on co-operative partnership. Clearly what has transpired in the intervening years has not achieved this aim, although the magnitude of the task should not be underestimated.

One of the most important lessons that was learnt from the work reported in the previous chapter was that the nature of design cannot be understood by simply reading the literature. Design is solution focused and it is through the production of alternative solutions that the nature of the problem is revealed. So it was in the spirit of this approach that a decision was made to undertake a study of design practice. The aim of the study was twofold: Firstly to inform the design of the proposed computer based tool. In particular, to identify how traditional design tools are used over the course of a project, the changing roles that they play, how they interrelate with each other and how the proposed support tool would fit within such an ensemble. Secondly to better understand the 'actual' use of design tools throughout a project. Such a study would, it is contended, provide an important grounding for the research. Thus, if the design of technological artefacts is to move toward supporting the early phase of design, then a necessary foundation will be to study both the practices of designers and more particularly their use of existing tools.

A number of studies have addressed the issue of design practice through the investigation of expert designers (Candy and Edmonds, 1996, Cross and Cross, 1996, Lawson 1994 and Roy, 1993) and have contributed to an increased understanding of the processes underpinning creative design. The study reported in this chapter differs from the previous work in two important ways. Firstly, it investigates the behaviour of student designers as their interaction with design tools was thought to be more explicit than that of experts. This notwithstanding, it is acknowledged that expert usage of design tools could vary significantly from that observed among student designers. Secondly, a tool mediated perspective is adopted through the explicit study of existing tools and how these influenced the way designers conceived of tasks and, as a consequence, how they think about the activity of design. In short, the aim of this study was to understand better the use of existing tools within design and thereby contribute to the design of future software tools aimed at supporting the early phase of the design cycle.

5.3 Method

As part of the B.A. in Interior Architecture at Napier University, final year students undertake a design project in the second semester. The projects typically address the re-design of an existing building. Three students agreed to participate in a series of fortnightly interviews during the course of their projects. It was decided to use a semi-structured interview approach during the studies for two main reasons. Firstly it provided a flexible method of gathering data that could be easily adapted to any changes that might arise during the lifetime of the study, and secondly, it required little preparation and minimal inconvenience on the part of the designers. Furthermore, Visser (1992) while discussing empirical studies of the design process made the distinction between task and activity. Task, she argues, refers to what subjects are supposed to do or the task that they set themselves. Whereas, activity refers to the way that subjects actually realise their tasks at the cognitive level (e.g. through the use of knowledge sources and the use of tools). Visser suggests that interview can provide data concerning the task, however data on the cognitive level can only be inferred by observation or verbalisation. It was with these provisos that a semi-structured interview approach was adopted. Each participant was assured that the study would not impact on the final mark allocated to their project. Interviews were conducted in the designers' normal working environment over a 16 week period and were videotaped. Typically each interview lasted in the region of 30-45 minutes, although the interviews tended to be longer during the early part of the projects. What follows is an account of the activities undertaken by each of the designers as they sought to complete their respective projects.

5.4 Case Study 1: A ski centre

This project concerned the refurbishment of the visitors' centre at the Cairngorms Ski Centre, a four floor 1980s building situated on a slope. The aim of the project, as stated by the designer, was to alter the circulation pattern of the space. Initially a physical model (Figure 5.1a) was produced to enable a better understanding of the space and critically to provide a means of visualising the relationship between each floor of the building. The act of building the model provided an opportunity to reflect on the design, while the completed model provided a tangible representation of the building, which could be physically manipulated by the designer in conjunction with the production of plan drawings. As a means of generating ideas, the designer produced reduced scale plan and sectional drawings (Figure 5.1b). The designer commented that the reduction acted as a focus, and concentrated the mind on the task at hand, and provided less opportunity for interruption due to the speed of production. Once a number of these alternatives had been generated, usually 4 to 5, the cycle was completed by drawing the chosen solution to scale.

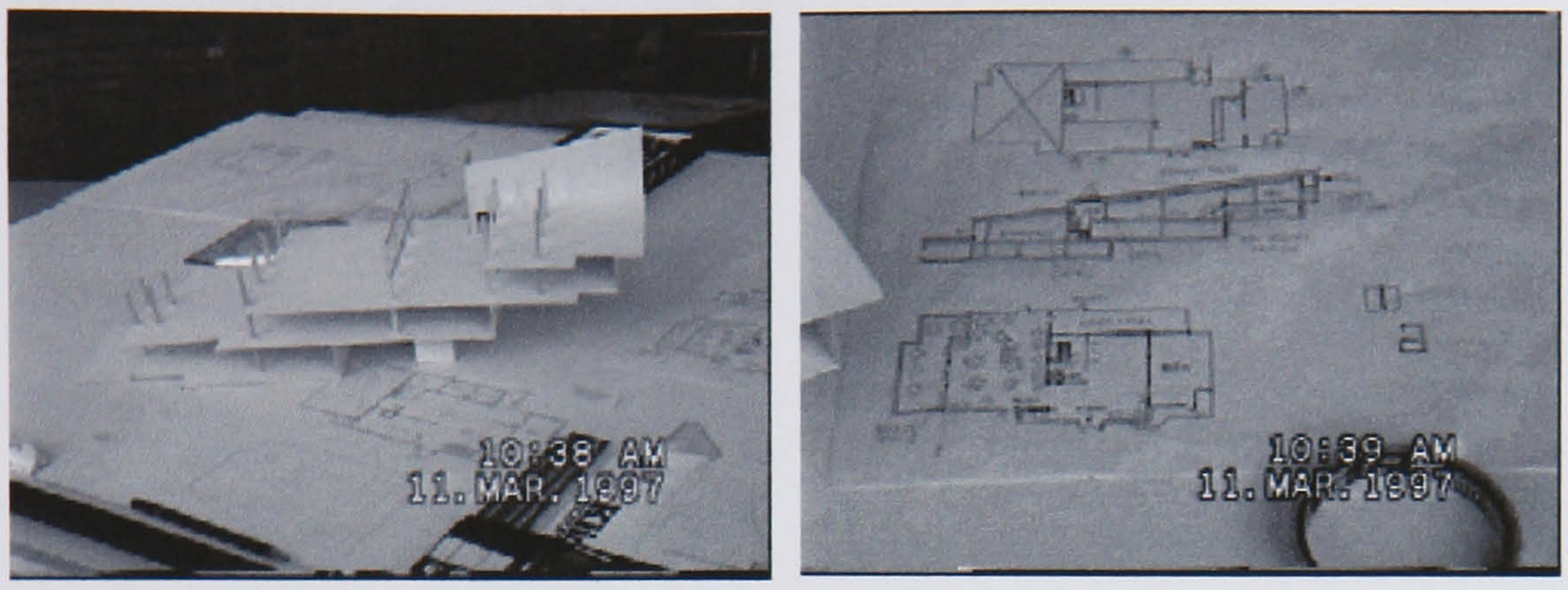


Figure 5.1 (a) Initial model and (b) reduced scale plan and sectional sketches of the building.

To illustrate volumes of space, a series of diagrammatic models were produced and colour was utilised to indicate particular attributes of the internal space. Figure 5.2 illustrates such a model that was produced later in the design process in order to clarify the demarcation of private and public space within the building. It was interesting to note that, as a result of producing this model, a decision was made to locate all the public spaces to the front of each level of the building. The designer commented that she considered the act of constructing such a model as central to this design decision. The rationale for such models was one of speed of development. For instance, rather than including all walls, colour could be quickly applied to distinguish location and functionality. The ability to rapidly articulate design ideas in tangible artefacts, which could then be examined and discussed, whether in the form of sketches or models, was a recurrent theme during the early stage of the design activity. The models were described as having two main purposes, that of enabling *exploration* of the problem and providing a basis of an *explanation* of the problem.

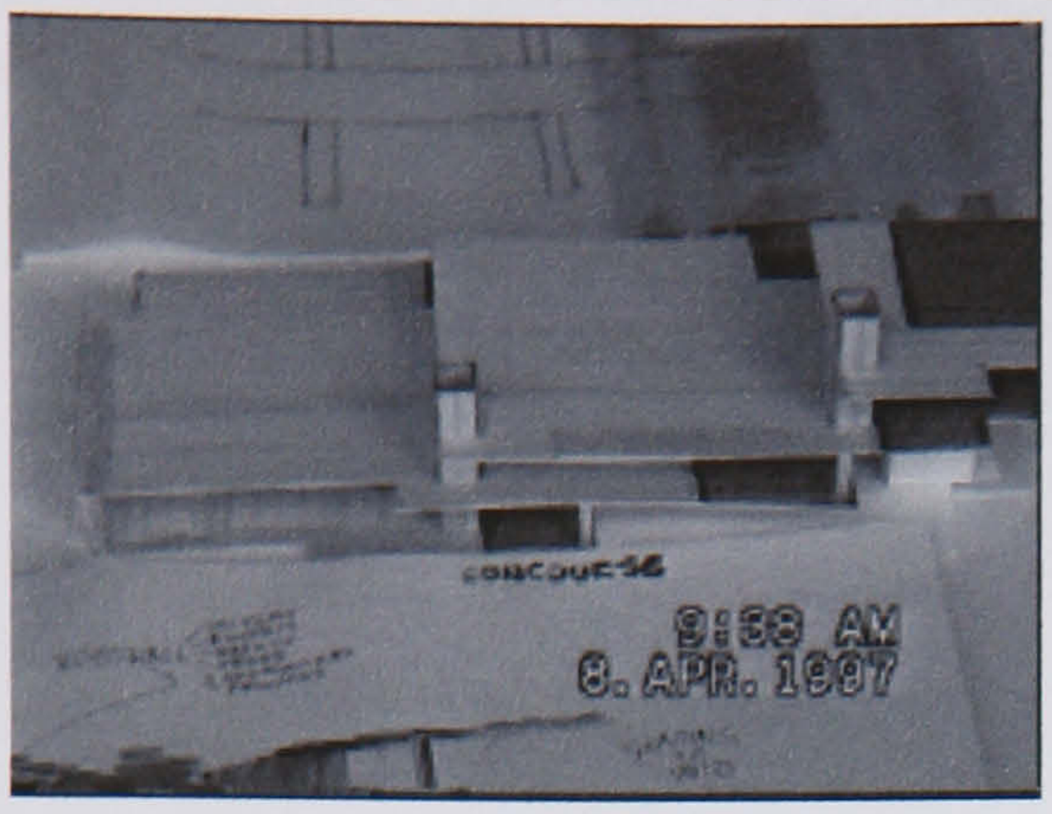


Figure 5.2 Diagrammatic model using colour to represent the demarcation between private and public space.

As the design progressed an increased number of sectional drawings were produced which were indicative of an important transition phase in the design. The move from rough sketches which, by their nature reflected a degree of uncertainty in the designer's mind, to the formality of the sectional drawing suggested an important crystallisation phase. As a complement to this activity, a number of small scale internal perspectives were produced. These were primarily internals of the building which were coloured to aid clarity. The sketch in Figure 5.3(a) was one of a series of drawings produced in order to visualise the main public area of the building and to consider the requirements associated with such a space.

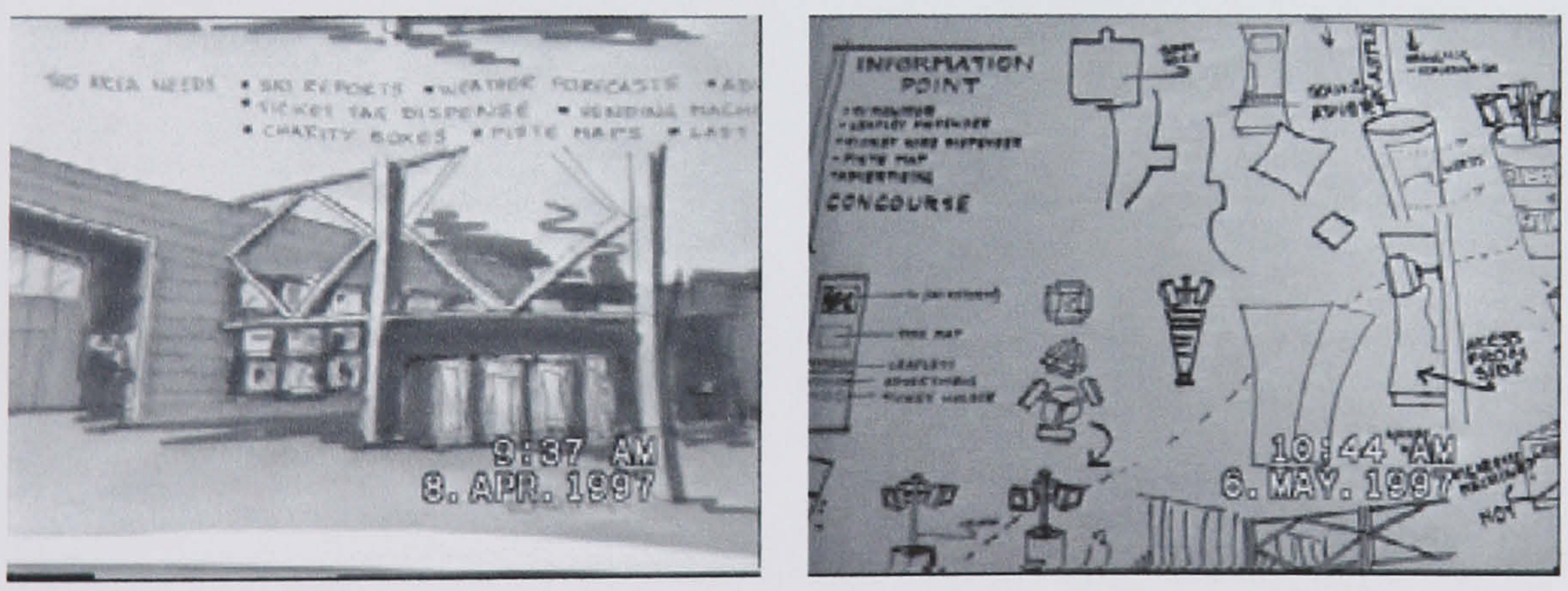


Figure 5.3 (a) Rendered perspective of the main public area and (b) examples of concept sketches for information holders.

A further element of the design was prompted by the realisation that the public space would have to meet certain requirements associated with the overall function of the building, for example the provision of tourist material. Early attempts to design holders, for paper based information material, focused on the use of metal pillars which supported the structure and the development of pod like containers which could be fixed to the pillars. The concept sketches for these elements were produced using a markedly thicker pen (Figure 5.3b), which was considered to be quicker and better for the consideration of the overall form. The sketches were annotated and acted as a means of articulating not only the form of the furniture but also the possible function.

The sense of design progression was further suggested with the production of a more detailed balsa wood model of the building. Each floor was constructed separately and could be removed to reveal the layout of the lower floors (Figure 5.4). Interestingly the material chosen to construct the model influenced the designer's thinking about the choice of finish for the building.

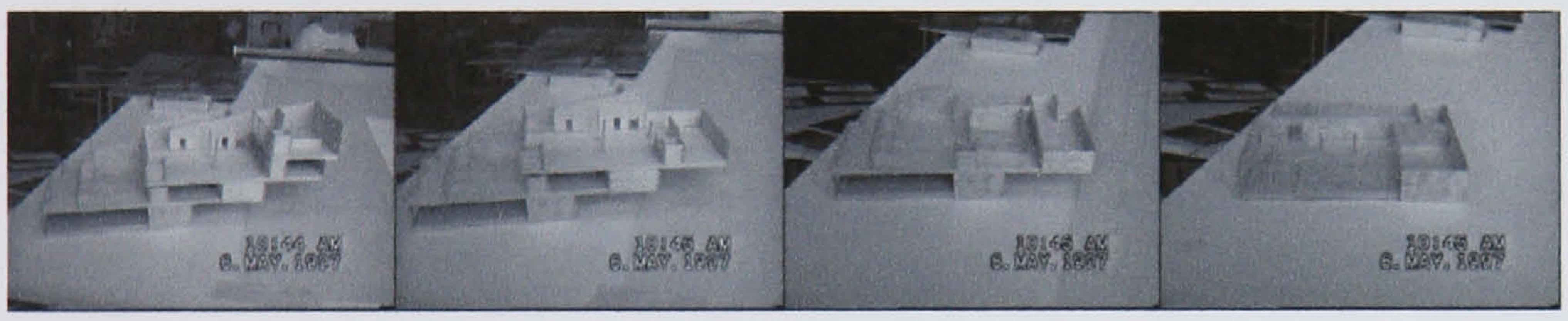


Figure 5.4 Balsa wood model enabling the visualisation of each floor within the building.

The model enabled the designer to view the building with a natural wood finish and the overall effect was considered to be more appealing than the original idea of utilising colour. The change of approach illustrated the profound influence that model making can have on a design solution, by both enabling the designer to view and manipulate the design, but also to implicitly reflect on the design while constructing the model and so open up new avenues of thought not perhaps available when drawing.

5.5 Case Study 2: Accommodation and gallery space for artists.

This project involved the refurbishment of an 1813 warehouse in the Leith district of Edinburgh. The building consisted of four stories that, together with a bonded vault basement, formed an enclosed block. The aim of the design was to create alternative housing, design studios and a gallery where artists could both live and work. The designer described the aim of the project as follows:

'the creation of a community that lives and works but also invites the public in.'

The initial planning stage of the design was characterised by the construction of a series of development models (Figure 5.5), with the purpose of enabling a better feeling for the actual space and possible locations of elements within the building.

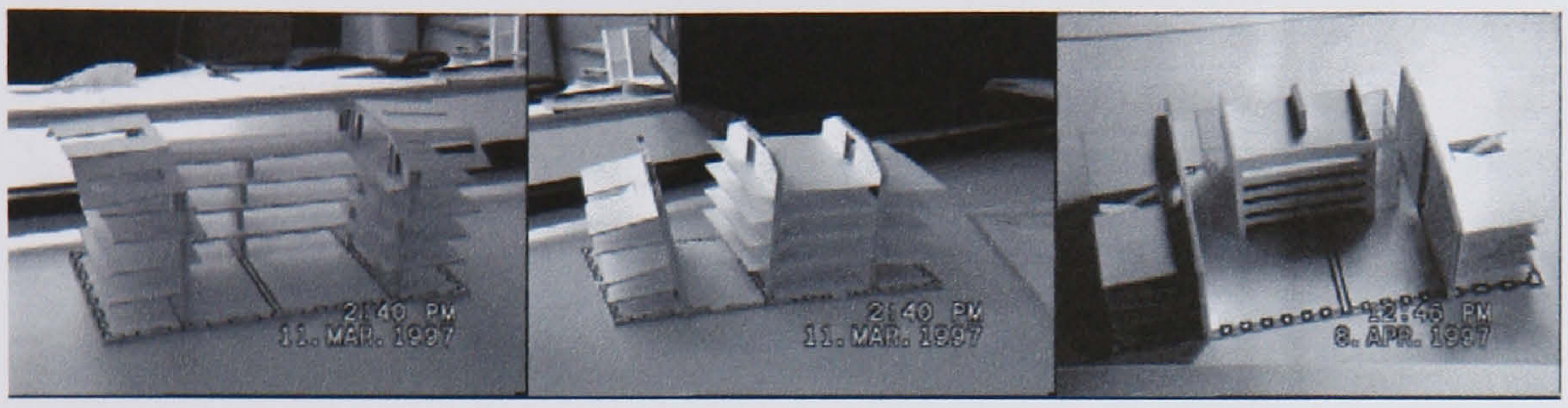


Figure 5.5 Initial development models

As part of this phase a model was developed using a CAD system[1]. The designer considered this as vital to the study of both size and scale of the building. This activity, referred to as 'building', provided a means to reflect on design ideas. Interestingly, the explanation provided for both the development models and the CAD based model were similar, namely that of enabling a more detailed understanding of the proportions of the space. The CAD system was considered to have the further advantage of enabling visualisation due to the ease and speed with which views and sections could be created.

The planning phase was characterised by a two stage process where development ideas were sketched by hand and then input into the CAD system. This second step enabled the designer to accurately visualise how the proposed element might fit within the building. It was only after the successful conclusion of this activity that the designer felt that the idea could be incorporated into the ongoing CAD model of the building. The ability to save the model of the building and then to use it as a basis for exploring the viability of alternative designs was an important facility provided by the use of CAD. Interestingly, this process appeared to occasionally act as a catalyst for the generation of new ideas. This might be linked to the speed at which perspective views could be generated and the

[1] The CAD system used by the designers in Case Studies 2 and 3 was Architrion V5.8 produced by BAGH of Canada.

greater understanding of the building space and proportion that these offered. The approach was succinctly summarised by the designer in the following phrase:

> 'precision is everything.... if I put it on the computer then I will know for definite'.

The designer summarised the advantages of CAD as follows: the explicit accuracy associated with output; the fact that such output could be used as the basis for freehand sketches; the resulting speed of idea articulation; and the production of cleaner, clearer drawings, which aid the communication of ideas. Two problems were also identified: firstly, the continual need to zoom in and out, resulting in the loss of sight of the building and secondly the problem of information loss due to its location in various layers of the CAD model. A possible solution to the initial problem was suggested when the designer commented that,

> '...it's as if the computer screen should be the size of your whole desk'.

These comments were considered to be indicative of the integration of CAD into the designer's repertoire of visualisation tools, the output from which is illustrated in Figure 5.6.

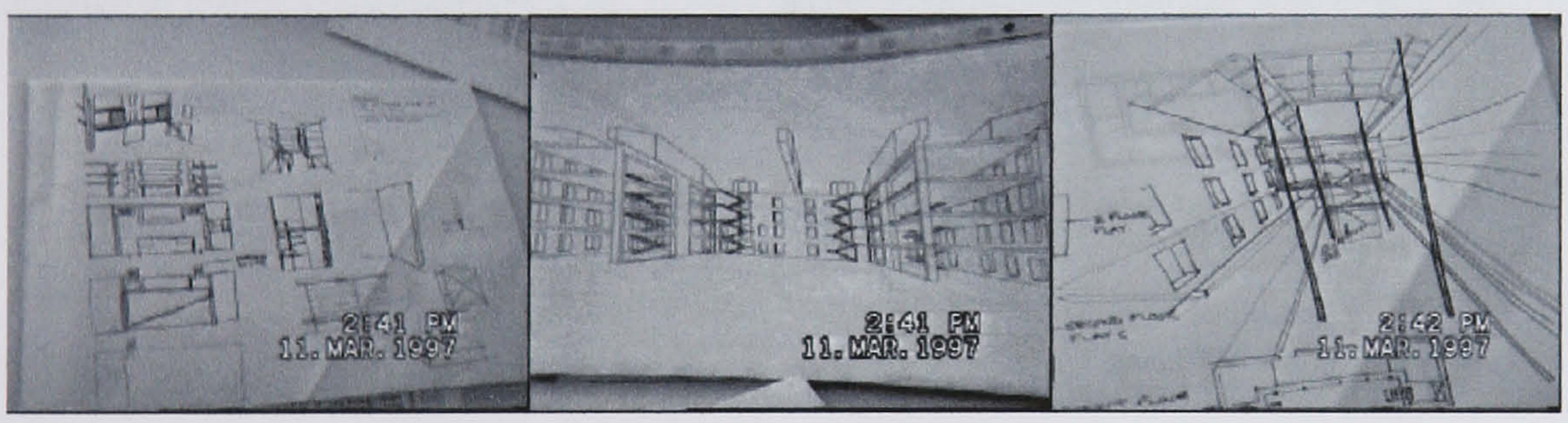


Figure 5.6 Examples of an early freehand sketch, a perspective view generated by CAD and a combination of the two techniques

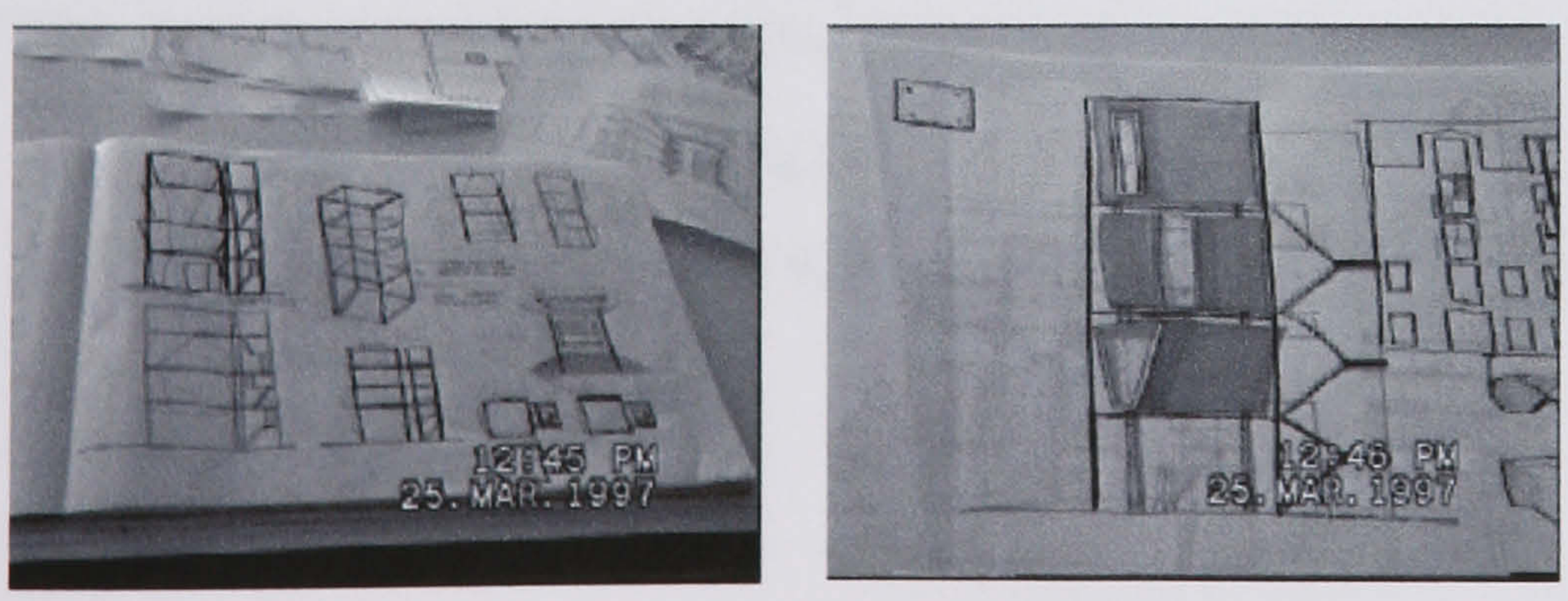
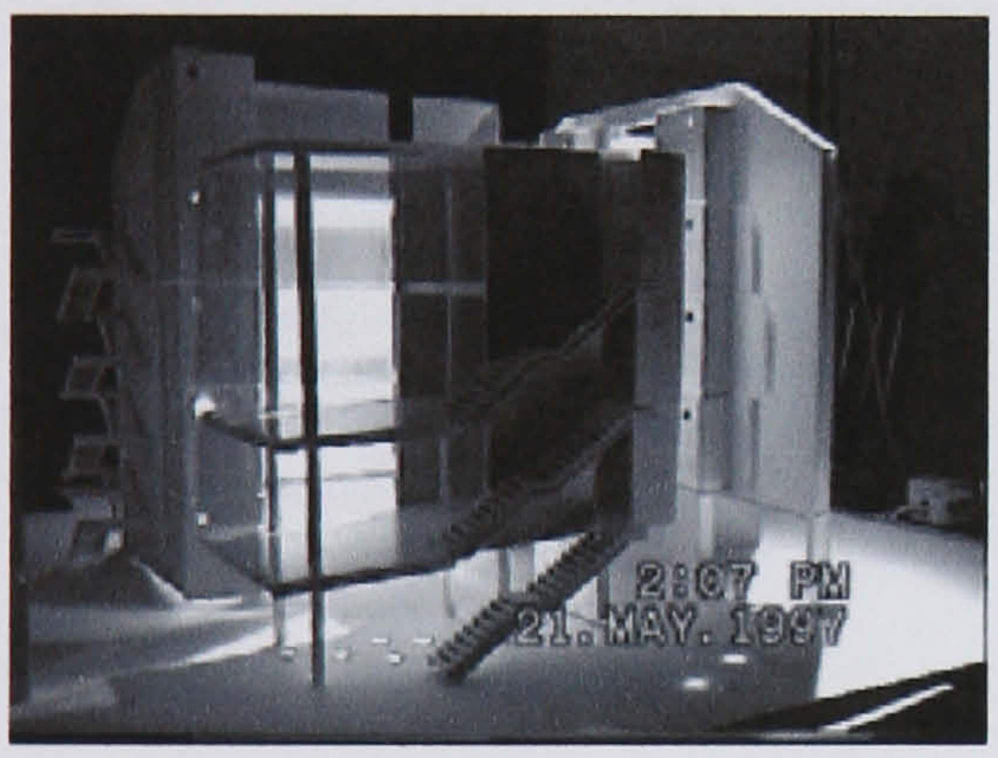


Figure 5.7 Development sketches of the proposed gallery

The proposed gallery design posed problems throughout the project. Previously the decision had been made to place the gallery on stilts in order to enhance the overall feeling of openness within the courtyard. Examples of development sketches are provided in Figure 5.7. Critically, the decision was made to set the structural columns back within the gallery itself thereby reducing the sense of heaviness associated with the structure. Internally the gallery was felt to be overly complex. For example, one idea was to incorporate moving partitions. These ideas were developed by means of a balsa wood model, which was later rejected. Interestingly, a physical model was built to enable the consideration of the problem in the context of the whole structure, whereas CAD drawings were felt to sometimes fail to include certain elements that might impact on the viability of the idea. The conclusion of the design was marked by the completion of the gallery and its integration into the building complex (Figure 5.8).



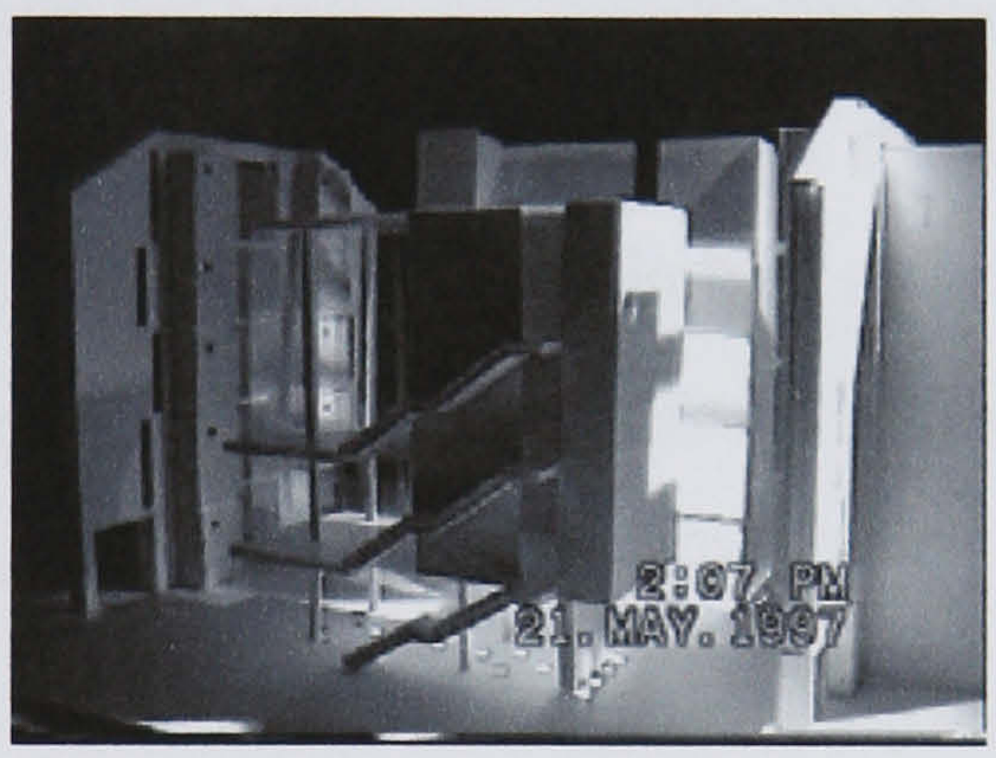


Figure 5.8 A lit model of the building and gallery complex

5.6 Case Study 3: A recording studio.

This project addressed the refitting of a 1912 building in Glasgow into a recording studio. The building comprised a basement and a ground floor. Initial concept drawings were produced by tracing the original plans for the building (Figure 5.9). These drawings facilitated visualisation and were a preliminary activity prior to the generation of scale plans.

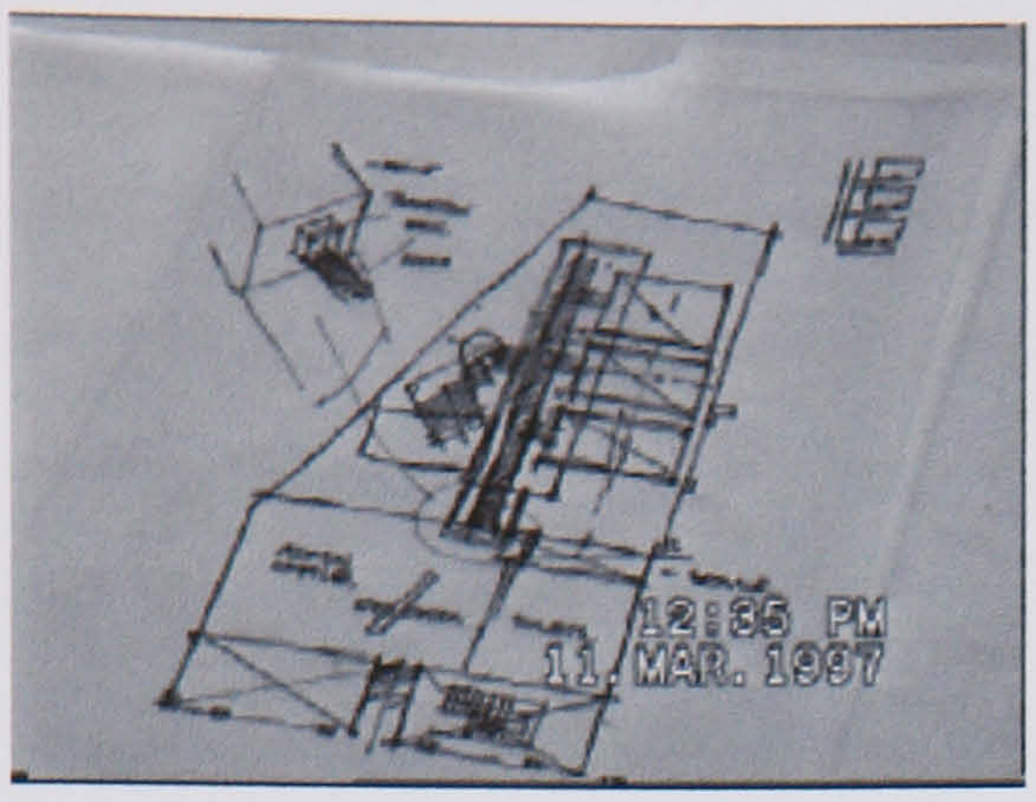


Figure 5.9 2D plan concept drawing

At this stage a physical model was constructed with the purpose of enabling the designer to manipulate and consider the building space. The designer also expressed a desire to utilise CAD early in the design process, but admitted that there was no intention to use it for planning, only for visualisation. The designer described a number of advantages offered by the building of physical models against those of CAD: faster to produce, although this was later acknowledged as possibly due to the designer's inexperience with the use of CAD; the ability to physically manipulate and therefore visualise the space; particular elements could be added in order to get a feeling as to their viability and finally the ability to generate a photographic record of the model's development. The designer concluded by making the following distinction:

> 'physical models are good for manipulation. CAD provides the illusion of manipulation.'

In order to facilitate the planning phase of the design, in particular the location of equipment associated with a recording studio, the designer opted to use freehand plan sketches but acknowledged that these were not to scale and there was always an element of doubt as to whether the planned layout would indeed fit into the building.[2] Plan sketches produced by freehand were used to visualise possible layout combinations as these were considered to be fast and easy to produce. The designer's strategy was to iterate through the sketching process in conjunction with building the physical model. This phase of the design would be completed by 'building' the model in the CAD system

[2] The designer in Case Study 2 considered the role of CAD as being integral to this process specifically because it addressed the issue of precision associated with design ideas.

for the purpose of generating perspectives. A hand rendered version of one such perspective is provided in Figure 5.10. This method was reported as being quicker than building a physical model and the designer commented on the ease of calculating the perspective viewpoint. The ease with which CAD could generate more complex perspectives was viewed as a positive advantage and it was considered that the interpretation of such drawings was increased markedly when rendered by hand. The designer commented that such perspectives appeared to provide a similar level of both explanation and exploration as physical models. CAD was seen as adding the further advantage of enabling the validity of concept ideas to be easily checked in the context of the scaled building.[3]

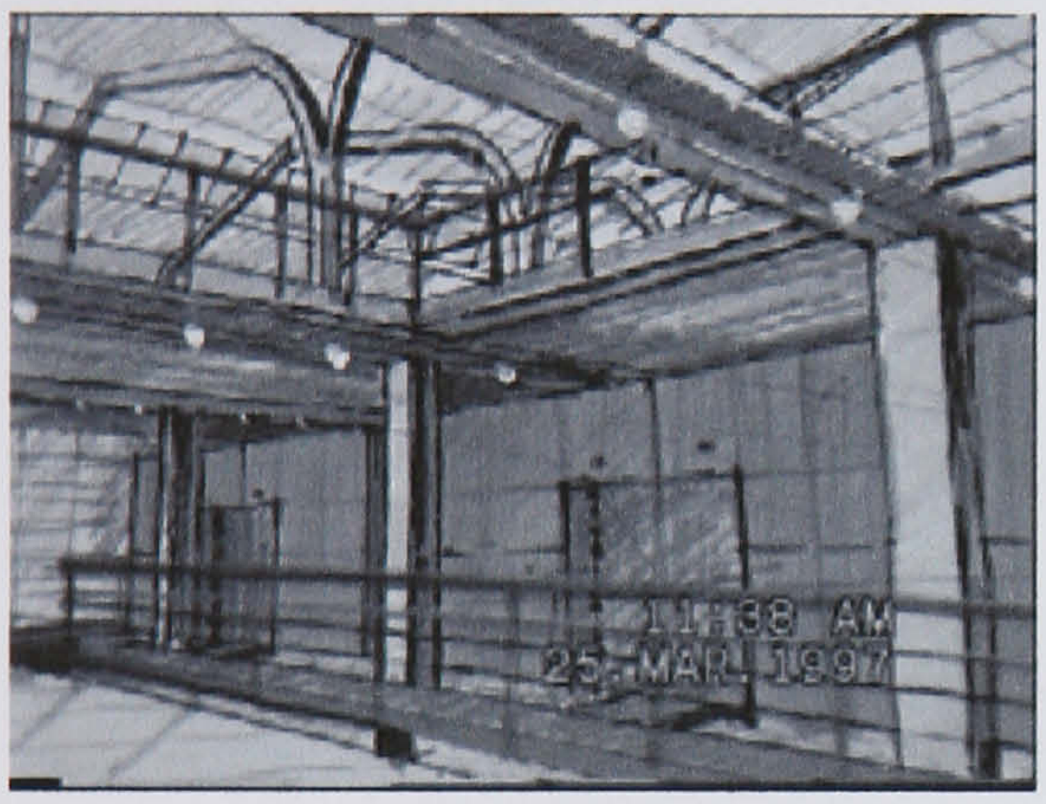


Figure 5.10 Perspective drawing produced by CAD, then hand rendered

Throughout the project the reception area of the recording studio remained problematic. Late in the project some major amendments were made to its layout. The rationale for this reflected a dissatisfaction with the previous solutions but, perhaps more interestingly, revealed an acknowledgement of the designer's difficulty in breaking out of the previously unsuccessful ways of thinking about the problem. In their own words:

> 'I just had an idea and stuck with it maybe I should just ... every time I did a new drawing I just used that (idea). I should have just started again'.

[3] The designer in Case Study 2 used a similar procedure for validating equivalent concept ideas. Critically, the level of detail associated with the freehand drawings of the designer in Case Study 3 was much higher than those produced by the designer in Case Study 2, prior to inputting the information into the CAD system.

The revised layout for the reception area now included an opaque glass panel that divided the private offices from the public reception area (Figure 5.11). It was envisaged that such a panel would incorporate lighting from below. A series of elevations were produced to explore the validity of the solution. The resolution of this issue marked the completion of the design.

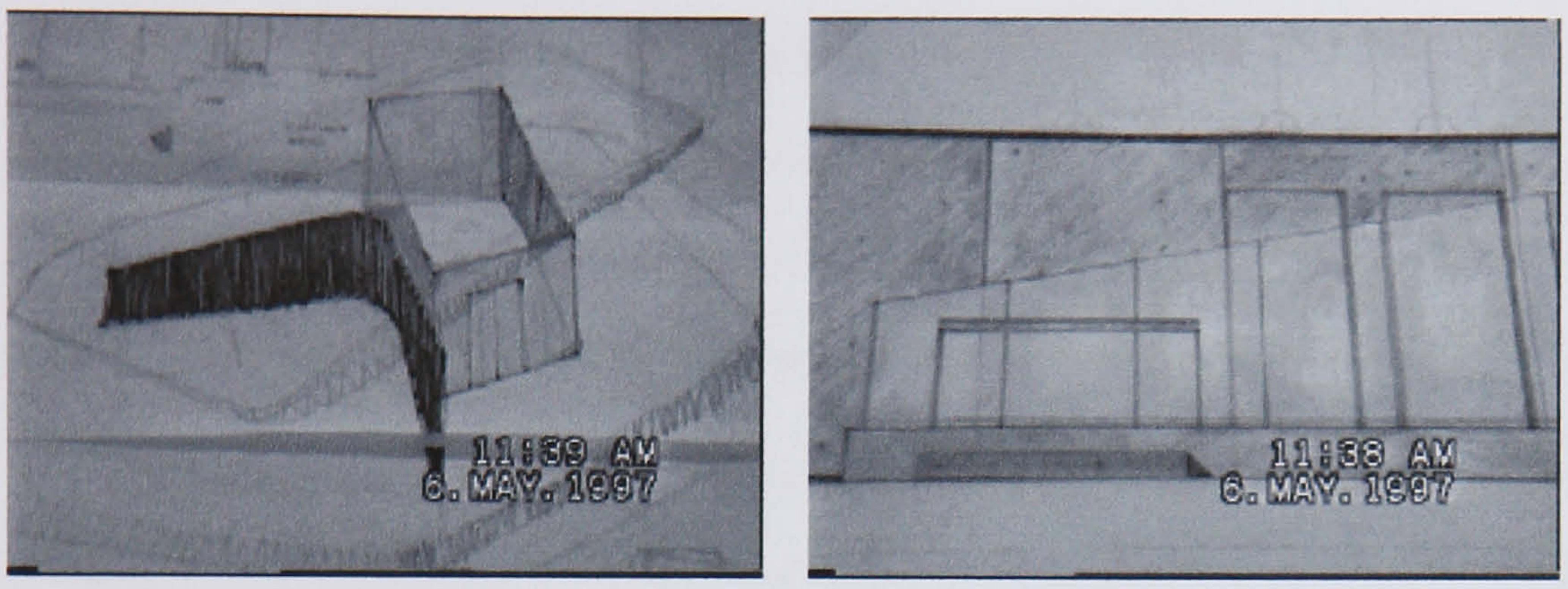


Figure 5.11 Development sketch and rendered elevation of partition in the reception area

5.7 Conclusions

Based on the case studies the following conclusions were made:

- design tools enable visualisation of ideas and provide a vehicle for expression and exploration;
- design sketches play a central role in the early phase of the design process;
- design thinking is reflected in the type and nature of tool usage;
- the haptic qualities of physical models provide the designer with an enhanced sense of engagement.

5.8 Discussion

A recurrent theme of the case studies was the support of visualisation offered by design tools. Visualisation was characterised in relation to the designer where it was conceived of as a means to explore the problem at hand and in terms of the client where it was described as providing a vehicle for explanation of the design. The study revealed how the designers conceived of the roles of these tools within the design process. Perhaps the most ephemeral were attributed to the part played by physical models which were characterised as enabling the consideration of the problem in the context of the whole building, rather than the more limited views provided by freehand drawings and CAD. A further quality attributed to physical models was that they enabled the designer to manipulate through touch a 3D representation of the building space. The sense of engagement provided by such models was viewed as something qualitatively different to that provided by drawings, whether produced by hand or by CAD. The characterisation of the designer as 'thinking with their hands' while creating or manipulating physical models supports the findings of Candy & Edmonds (1996) and Roy (1993) and echoes the sentiment of Schön (1983) when he described the act of freehand drawing in terms of the designer conversing with an image. Such an intimacy between the designer and the tools for visualisation will clearly have a profound impact on the nature of input/output devices associated with technology aimed at supporting the early phase of the design cycle.

Throughout each of the case studies freehand drawing always took place. In the early creative planning phase of the design, drawings were usually in the form of 2D plan sketches loosely based on existing architectural plans. While varying in terms of scale and degree of content, these sketches enabled a rapid articulation of design concepts. The complementary features of flexibility and speed, associated with hand drawn 2D sketches, were considered by each of the designers to be critical factors during this phase. In particular, their ability to support the parallel lines of thought necessary for the exploration of alternative design solutions and the marked changes in tempo characteristic of this phase of design. The latter observation supports the findings of McNeil and Edmonds (1994). As design concepts became more concrete, different drawing techniques were adopted. Sectional and perspective drawings played an important role in both identifying and checking planned elements within the building space. Freehand sketching still took place and was indicative of the interplay between abstract and concrete ideas throughout the design cycle. The use of CAD provided advantages in terms of speed and ease with which perspective views could be generated, although it was the more experienced designer in the second case study who employed the technology earlier in the design cycle. This designer had over a period of time developed a sophisticated method for integrating the rigidity of CAD into a process for the validation of early concept ideas.

5.9 Technology and Design: A Co-operative Partnership

The requirement for visualisation of both the problem domain and partial solutions was a theme that emerged from this study. Freehand drawing, physical modelling and CAD achieved these in particular ways. Both in terms of their representation and their consequent ability to portray certain elements of the problem, and also by their engagement of the designer during the process of production. The process for achieving visualisation is as important as the end product itself, particularly during the generation and selection of alternative solutions. Indeed, the ability to both generate and present alternatives represents a critical juncture in terms of both the design process and co-operative behaviour.

In the context of design, Donald Schön (1983) described the presentation and acceptance of alternatives as a move from the 'what if' to a decision that becomes a design node. Design nodes provide a platform with implications for further decisions. Thus there is a continually evolving system of implications within which the designer 'reflects on action'. Similarly, a principal element of co-operative behaviour during problem solving is the creation and maintenance of an environment where solutions can be refined through logical argument and the resolution of different perspectives. Through such discussions the very essence of the problem will be revealed. Essential to this view of co-operative behaviour is the ability of any participant to generate and communicate alternative solutions, as it is these which will spark the iterative process implicit in co-operation (Broadbent, 1973). Alternatives and partial solutions become the currency of communication. In short, different but sympathetic beliefs are vital to a successful and productive co-operative relationship.

If design is conceived of as an active co-operative process, where the role of alternatives are pivotal to progression within the conceptual phase, then it is critical that this issue be addressed by technologists. One mechanism for generating alternative solutions is a Shape Grammar, as proposed by Stiny (1975). This technique seeks to formally represent the rules and objects associated with a particular design style. In terms of its application to technology the approach offers a number of advantages: a method for formally representing existing design styles; a generative capability and an opportunity to apply the reasoning capabilities of knowledge based systems. These rules can be used to generate new shapes in the language of the original. Furthermore, by the provision of a 'meta-grammar', it would be possible to provide designers with a mechanism whereby transformations could be applied to produce new shape grammars defining new styles. The next chapter will introduce the concept of shape grammars as a technique for the representation and manipulation of design styles.

6 An Introduction to Shape Grammars and their Application within Design

6.1 Overview

This chapter will introduce the following themes:

- an introduction to shape grammars and their relevance to the thesis;
- an example of a basic shape grammar;
- the transformation of shape grammars;
- a description of relevant computer based implementations of shape grammars.

6.2 Introduction

Design is founded on the expression of ideas, without such expression it becomes meaningless. One method for achieving such articulation is through drawings. Indeed the analogy of drawings acting as a language of design has been discussed in an earlier section of the thesis (see Chapter 4, Section 4.6). Indeed, if one takes the analogy further design can be thought of as a language that is constructed from a grammar. Thus designs of a given style could be generated from a grammar. Such an idea is appealing not just within design, but within any field seeking to harness a generative capacity.

Initially the concept of grammars was popularised through the work of Noam Chomsky in the 1950s, in particular the concept of a 'generative grammar' as a means of characterising natural language. That is, the idea of using grammar to express abstract ideas. Chomsky (1957) defined grammar as follows:

> 'a vocabulary of symbols or words, together with a set of rules that specify how elements in the vocabulary may be combined to form strings of symbols, or sentences in a language'

In the next decade research in the field of computer automated recognition (e.g. Kirsch, 1964) sought to utilise grammars as a means of analysing images. Within the field of architecture there were increased moves away from the traditional case study, where the concern was with descriptive examination, to the search for principles of design. The underlying objective being to make architectural knowledge and its teaching explicit and to facilitate the intellectual appropriation of formal precedents in design (Wojtowicz & Fawcett, 1986).

An example of this approach within architectural theory was Alexander's 'pattern languages' which consisted of informal, verbal rules for the generation of architectural and urban designs (Alexander, 1977). While this grammar was devised for generative rather that analytic or recognition purposes, its rules were primarily verbal, rather than pictorial and also lacked the formal precision and rigour required to make any such language appropriate to form the basis of a computer based support tool.

The traditional view of grammatical models provided the basis for the first comprehensive model for two and three dimensional forms. In the 1970s, shape grammars that generate languages of designs were developed by Stiny and Gips (1972). Where grammars in logic and related areas manipulated symbols, shape grammars manipulated shapes. Thus shape grammars were founded on a vocabulary of shapes and a set of spatial relations that correspond to different arrangements of shapes within the vocabulary. A shape grammar comprises of an initial shape, together with a set of shape rules that describe the spatial relations between the shapes. The rules are applied repetitively or recursively to the initial shape and to the consequent shapes that are generated as part of the language.

Shape grammars have a number of attributes that are considered to be pertinent to the research being undertaken. They are as follows:

- the grounding in a design tradition;
- the capacity for representing design styles;
- the potential for a generative capacity.

6.3 A Basic Shape Grammar

This section will illustrate the use of a basic shape grammar in the context of architectural design. The grammar, together with the original figure, was first presented by Knight (1994). The starting point for the grammar is a Greek cross design, a typical Renaissance church design based on such a cross is shown in Figure 6.1(a). The basic cross plan can be described in a variety of ways, for example, as two overlapping rectangles of proportions 2 x 1. These shapes constitute the vocabulary of shapes shown in Figure 6.1(b). In order to produce a Greek cross, the shapes in the vocabulary can be put together to form the spatial relation in Figure 6.1(c). The vocabulary of shapes and their spatial relationship are used to define the shape grammar illustrated in Figure 6.1(d). The initial shape of the grammar is a shape from the vocabulary. The shape rule is based on the spatial relation and it enables the production of a variety of new and complex designs to be constructed in terms of one simple relation. The rule states that if a 2 x 1 rectangle – the shape on the left hand side of the rule – can be found in any size or orientation in a shape configuration that is being generated, then another 2 x 1 rectangle can be overlaid on top of it as shown on the right hand side of the rule. By repeated application of the rule, starting with the initial shape, a variety of different designs all based on the Greek cross, can be produced. Figure 6.1(e) presents the steps involved in the production of one such alternative design.

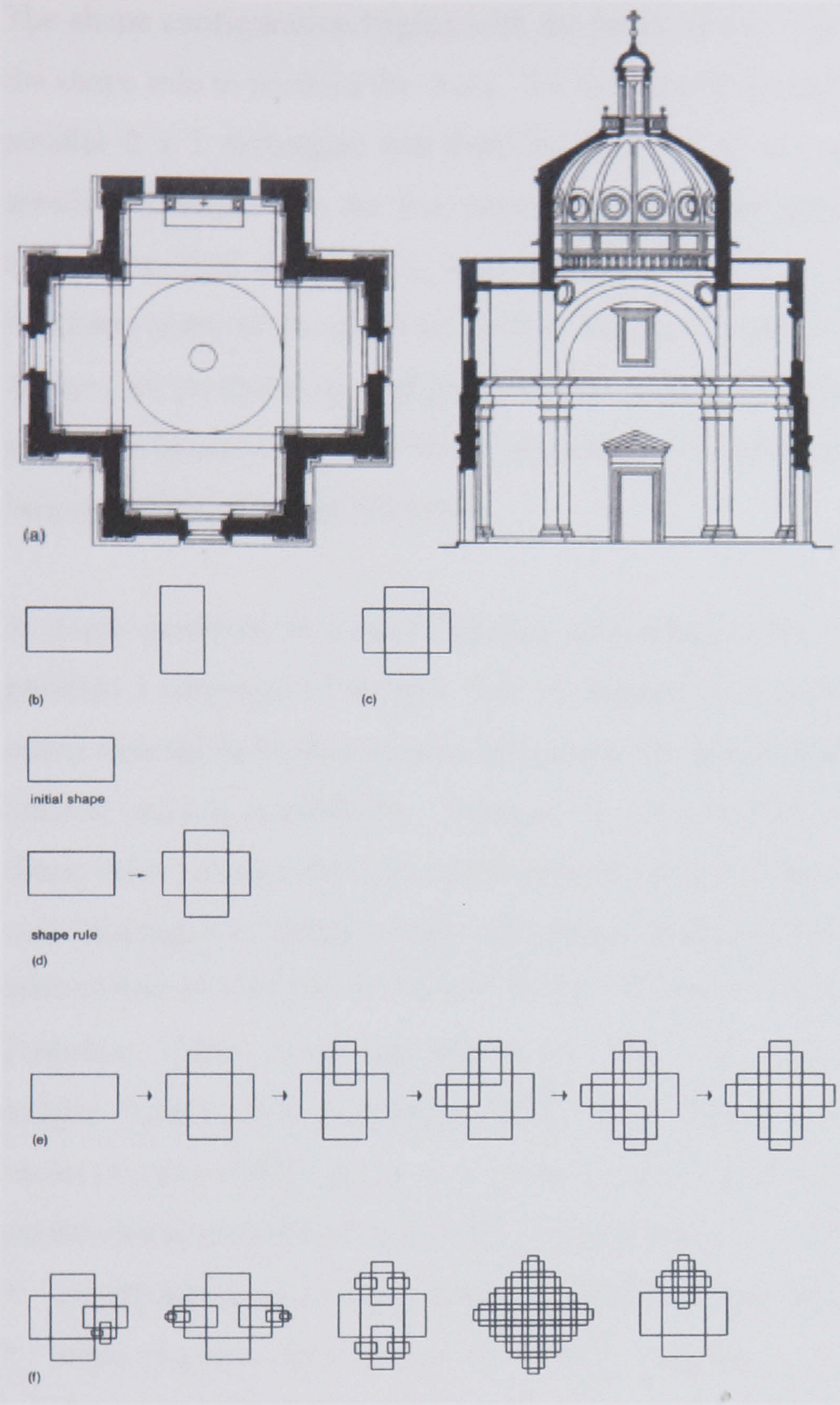


Figure 6.1 The development of a simple shape grammar based on a Greek cross design.

(a) Santa Maria delle Carceri, Prato – Guiliano da Sangallo

(b) Vocabulary of shapes

(c) Spatial relation

(d) Shape grammar

(e) An example design

(f) Designs in the language

The shape configuration begins with the initial shape. The first step is the application of the shape rule to produce the cross. An attribute of the Greek cross is that it contains four smaller 2 x 1 rectangles that form its arms. The rule is then applied to any of these smaller rectangles. In the four steps that follow the rule is applied to each rectangle in turn. The final design is a more elaborate version of a Greek cross. Figure 6.1(f) illustrates some of the different designs that can be generated by the grammar. Different designs are produced by applying the shape rule in different ways to different parts of the shape configuration as it is being generated. All of these designs are said to be in the language defined by the grammar.

A shape grammar is a set of precise generating rules which, in turn, can be used to produce a language of shapes. Just as linguistics is primarily concerned with analysis, rather than the invention of new languages, the initial application of shape grammars has been in analysis or criticism. Typically, a given building or style has been taken and the shape rules induced that can re-generate the given shapes. Rather than the generation of new languages of design, work with shape grammars has focused on the definition and articulation of designs in known styles. Examples from architectural design include, Palladian Villas (Stiny and Mitchell, 1978) and Frank Lloyd Wright's Prairie-style houses (Koning and Eizenberg, 1981) from furniture design, Hepplewhite-style chair backs (Knight, 1980) and from painting the work of de Stijl (Knight, 1989b). Such work on the characterisation of similarities is distinguished by the following:

- clarifying the underlying structure and appearance of known instances of style;
- supplying the conventions and criteria necessary to recognise whether any other design is an instance of the style; providing the compositional machinery needed to generate new instances of the style.

The same rules can then be used to generate new shapes in the language of the original. Just as linguistic grammars provide a finite set of rules capable of generating an infinite set of linguistic constructions (Chomsky, 1957), so shape grammars consist of sets of rules that can be used to generate infinitely many instances of shape arrangements that conform to the specified rules. Interestingly, the grammar describing the architecture of

Frank Lloyd Wright was used to generate new instances of buildings in the Prairie style, which experts couldn't discount as being produced by the architect himself. The rules are *replacement rules*, so typically state that if a spatial configuration contains a given sub-element then that element may be replaced by a new, specified, shape. The application of the rules begins with a given seed shape and can proceed in a non-deterministic manner. Furthermore, by making alterations to a given shape grammar the language of shapes can be modified in either subtle or radical ways. In this way it could be possible to model an incremental development of style. Knight (1981) has demonstrated how a shape grammar for a known style can be systematically transformed by the application of 'change rules' to produce new shape grammars defining new styles. The process of transformation is considered to be central to the production of design alternatives, which, in turn, are viewed as the lynchpin of the co-operative approach.

6.4 Transformation of Shape Grammars

The transformation of shape grammars can be achieved by three independent operations: rule addition, rule deletion and rule change, Figure 6.4. Rule addition and rule deletion are straightforward, involving either adding rules to a grammar or subtracting rules from a grammar in order to produce new grammars. In the case of rule change, grammars are modified in various ways to produce new rules of new grammars.

Rule addition, simply adds a new rule to a given grammar, such that all the original shape configurations remain possible with the addition of some new ones. Rule deletion is the inverse. It transforms a grammar by subtracting or deleting shape rules. The net effect of rule deletion is always a reduction in the number of possible shape configurations that it might generate.

Rule change is a more complex approach to the transformation of grammars, in that it can change shape rules, the initial shape, or the final state. The latter two options are not available to either rule addition or subtraction. Such changes are achieved by altering any of the spatial or non-spatial components of the grammar: spatial relations, spatial labels, or state labels. Changes to any of these components can result in either subtle or marked changes in the language that a grammar can generate. Changes to each of these elements will now be discussed.

6.4.1 State Labels

State labels control the order in which the rules of a grammar are applied so as to produce a shape configuration. These labels can be associated with the rules, the initial shape and the final state of a grammar. Changing the state label associated with each of these parts will have a variety of effects. With rules it can result in changes to the ordering and the number of times they are applied. In the case of the initial shape, it can affect which rule is applied first and finally in the case of the label associated with the final state it can impact on which rule is last to be applied. In short, altering the state labels of a grammar has the potential to change the ordering of rule application throughout the shape generation process, together with the application of both initial and final rules.

6.4.2 Spatial Labels

Unlike state labels, spatial labels can only be associated with the rules and an initial shape of a grammar. Changing the spatial labels of either of these components of a grammar can affect the shape configurations that the grammar can generate. Thus, while all of the designs produced by the rules are constructed in terms of the same spatial relation, different labelling of the rule will produce designs of very different characteristics. It was this aspect of spatial labels that the prototype systems, described in the next chapters, sought to take advantage off, as a mechanism for the generation of design alternatives.

6.4.3 Spatial Relations

Spatial relationships are the basis of the rules that comprise a shape grammar. These rules specify how the shapes can be combined to generate designs. The spatial relations used to define the rules of a grammar can be changed by replacing the shapes in them with other shapes. Two kinds of changes can be realised, firstly by replacing a shape in the relation with a geometrically non-similar one (i.e. introducing a new shape into the relation). The second type of change can be realised by replacing a shape in a relation with a geometrically similar shape (i.e. replacing a rectangle with a 90° rotation of the same shape). Thus a new spatial relation is produced by re-sizing or re-positioning a shape by means of translation, reflection, rotation or scaling.

Informally, these different ways of altering spatial relations have acted as a common source for inspiration within design. Figure 6.2 provides an example, again taken from Knight (1994), of the changing of shapes in a spatial relation while maintaining the overall arrangement of the shapes. Plans of three houses by Frank Lloyd Wright illustrate this technique. The plan of the Life house is composed of various spatial relations between rectangular areas serving different functions. The Jester house is created by introducing a new shape, a circle, in place of each rectangle, Figure 6.3. Similarly, the Sundt house is created by replacing each rectangle with a triangle. While each design looks very different, the arrangements of shapes in the underlying spatial relations are approximately the same, only the shapes in the relations are changed. The original insight behind this example is credited to March and Steadman (1974).

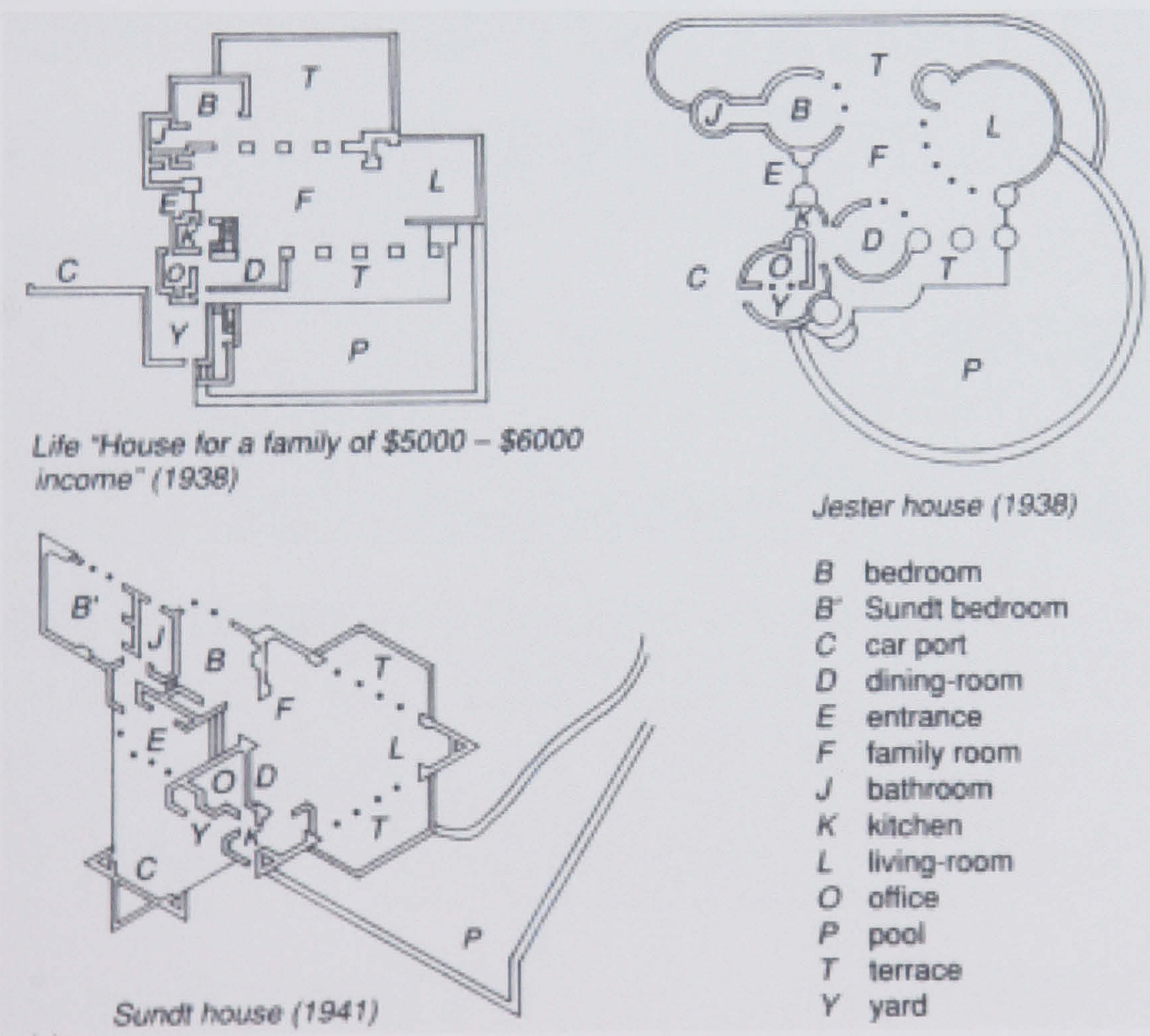


Figure 6.2 Three house Plans by Frank Lloyd Wright

Figure 6.3 Jester-Pfeiffer House, Palos Verdes, California – Frank Lloyd Wright (1938/71)

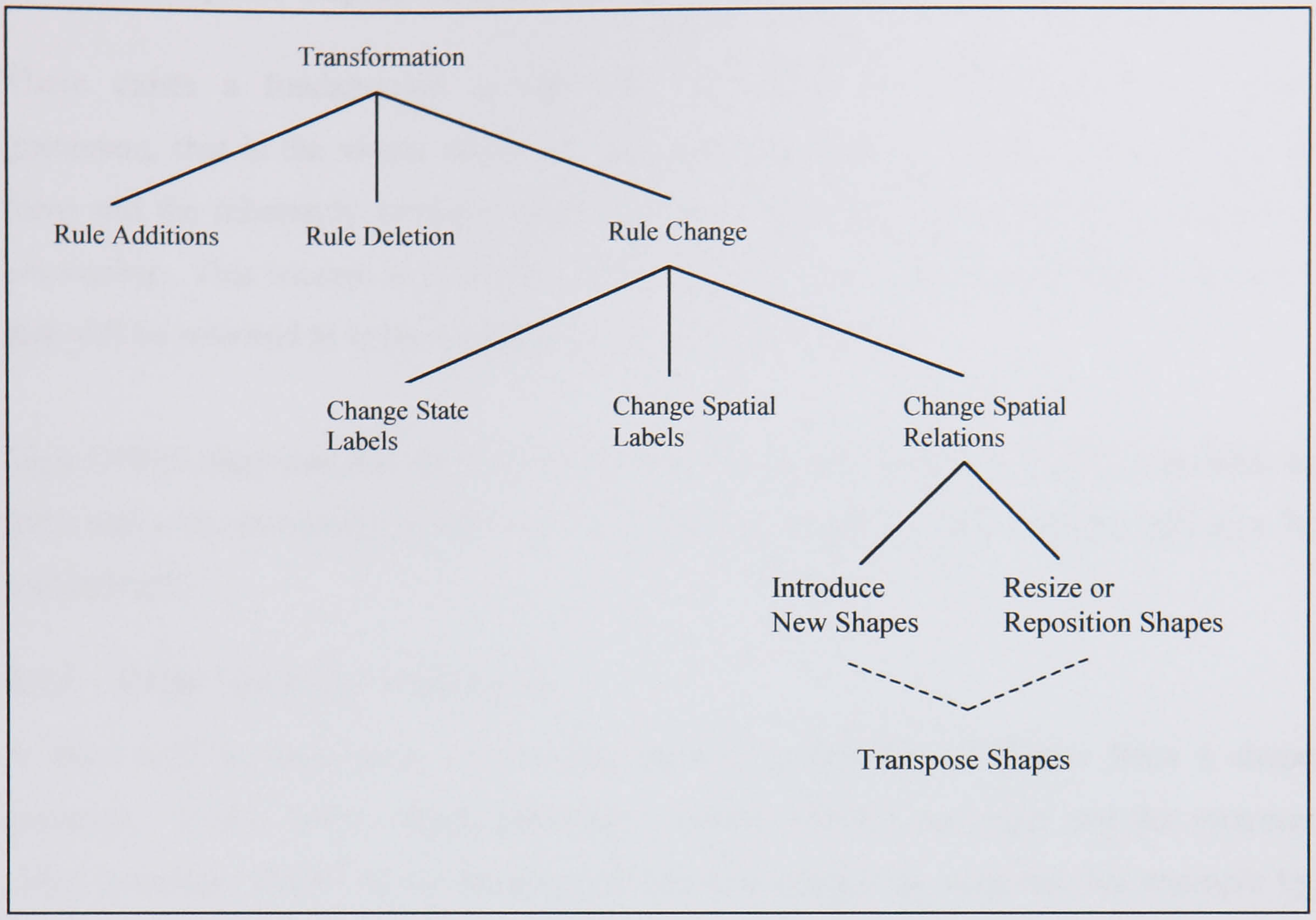


Figure 6.4 The different ways of transforming a shape grammar

Shape grammars offer a design based method that naturally lends itself to computer implementation. Furthermore, it offers a means of representing design styles in the form of spatial relationships. Crucially, shape grammars suggest mechanisms through which designers can interact with, and subsequently transform, the rules that comprise a grammar. It is through such 'change rules' that the generative capacity of shape grammars are revealed (Figure 6.4). It is for these reasons that shape grammars were selected as a vehicle through which to study further a co-operative approach to the support of the early phase of design, in particular, the role of alternative solutions and their capacity to spark the creative process.

6.5 The Computer Implementation of Shape Grammars

There exists a fundamental tension that underpins any implementation of shape grammars, that is the visual nature of such grammars and the people who want to use them and the inherently symbolic nature of the underlying computer representation and processing. This tension is primarily manifest at the level of the interface and is an issue that will be returned to in the remaining chapters of the thesis.

Gips (1999) suggested that an implementation of a shape grammar could be classified in three ways: an interpreter, a parser or an inference program. Each of these will now be summarised.

6.5.1 Shape Grammar Interpreters

A term used to describe a system that aids the generation of shapes from a shape grammar. In this case a shape grammar is coded into the computer and the program either generates shapes in the language or the user guides the program, for example by the selection of the rule to be applied and how it will behave during the construction of the current shape configuration.

6.5.2 Shape Grammar Parsing

A scenario for a parsing program might be that it is given a grammar and a shape. These are analysed and the system has to determine whether the shape is in the language of the grammar and, if so, it would ascertain the set of rules used to generate that shape.

6.5.3 Shape Grammar Inference

In this case the system would seek to determine a grammar which constructs a given set of shapes. A possible scenario might be that the program would be given a corpus of known plans of, for example, primary schools and would then automatically generate the appropriate shape grammar.

Not unsurprisingly, to date the majority of computer based implementations of shape grammars have been interpreters. Increasingly sophisticated prototypes have been developed in order tackle specific issues of the problem (Gips, 1975, Krishnamurti, 1982, Krishnamurti & Girand, 1986, Chase, 1989, Stouffs, 1994 and Tapia, 1996). These implementations have contributed to the identification of a series of research issues pertaining to the implementation of shape grammars. In the next section two of these, which have a bearing on the work reported in the thesis, are discussed.

6.6 Research Issues concerning the Implementation of Shape Grammars

In a recent symposium on design and computation, held at the University of California Los Angeles, (March & Tapia, 1999) a series of research issues were identified as associated with the successful implementation of shape grammars. Two of these are pertinent to the research presented in this thesis.

6.6.1 The User Interface

Interaction with a grammar is vital if it is to contribute to the design process. It is through such interaction that the designer will be able to engage in a dialogue with the self and thereby begin to explore the solution potential of the grammar. Setting aside the issues of how to present a grammar comprising of over 100 rules, the more fundamental issue is how will designers interact with the rules that comprise the grammar, as a means of transforming them, in order to discover its solution potential?

Tapia (1999), while discussing a possible new paradigm for a shape grammar system, suggested that the process of developing and using a shape grammar could be divided into several logical phases. The final phase he entitled, 'exploring the language of designs defined by the grammar'. This might be achieved, he suggested, by the designer generating designs, imposing additional constraints, halting the generation process, backtracking to a previous design, or simply saving the current state.

Whereas Flemming, quoted in Gips (1999), raised the issue of a shape grammar interpreter where the designer could parameterise the shape rules by means of visual interaction. This issue will be returned to in Chapter 8 during a discussion of the rationale behind the implementation of 'loose-fit' rules.

6.6.2 The Role of Physical Models

The role of physical models, in facilitating a greater understanding of the output associated with shape grammars, draws an interesting parallel with the thoughts of the author concerning the haptic qualities of design tools (see Chapter 5 Section 5.8) and at a wider level the role of the body in the design process. This final issue will be discussed in more detail in the final chapter of the thesis.

6.7 Shape Grammars, Co-operation and Prototypes

The aim of the remainder of the thesis is the creation of a prototype system that has the capacity to generate design alternatives, guided by the designer through interaction, and at a conceptual level appropriate to the early phase of the design process. Shape grammars are considered to provide a suitable mechanism for achieving such an aim.

In summary, shape grammars offer the potential to formally represent rules and objects associated with a particular design style and, critically, the opportunity to apply these rules thereby generating new shape arrangements in the language of the original. The remaining chapters of the thesis will present a prototype system implemented in Prolog and based on a simple shape grammar. The system incorporates the concept of 'change rules' in the form of labels. The purpose of the system is to enable the exploration of how such a representation could provide a designer with a 'meta-grammar' by which to manipulate a shape grammar and thereby explore a wider range of possible solutions. Through such manipulation novel ideas may be released to spark the creative iterative process vital in design. In short, shape grammars consist of a set of rules that can be used to generate infinitely many instances of shape arrangements. This can be considered as a 'state-space' from which alternative configurations can be found.

7 Prototype P1 - Supporting Design through the Strategic Use of Shape Grammars

7.1 Overview

This chapter will introduce the following themes:

- an introduction to the prototype system P1;
- a description of the use of 'spatial labels' within the prototype;
- a summary of three discussions with design professionals concerning the utility of the approach;
- a discussion of the conclusions drawn from the work;
- a description of the relationship between the prototypes P1 and P0;
- a discussion of further areas of research related to the prototype.

7.2 Introduction

This chapter will introduce a prototype system P1 that utilises a basic shape grammar to generate shape configurations. The prototype incorporates the concept of 'change rules', in the form of spatial labels, which act as a mechanism through which a designer can transform the behaviour of a grammar and ultimately the shape configuration that it produces. Within the prototype P1, spatial labels act as a 'meta-grammar' through which the designer can produce alternative designs. Two aspects of this are particularly important. Firstly, the alternatives should include *unexpected* solutions and, secondly, they should be reasonably likely to be evaluated as *good* solutions. The joint requirements for something to be both unexpected and good (by whatever definition) do not sit well together. However, the notion of a search space defined by a grammar offers an interesting possibility. A generative grammar can represent an infinite set of entities by finite means. Thus it is quite capable of generating something that is unexpected. On the other hand, the set of all possible results that can be generated is restricted to those that conform to the rules of the grammar. In that sense, it is possible to constrain what is generated to entities that might be judged *good*, providing that the rules are appropriate. In fact, no guarantee of unexpectedness or goodness can be given to the results of applying a generative grammar. It is contended that the probability of generating such interesting entities might be relatively high. Thus it is considered worthwhile to look into the use of such grammars in early design support systems.

In this chapter it is argued that finding a successful solution in design is often facilitated by the ability to generate and communicate alternatives. Within the design process the generation and selection of such alternatives plays a vital role both in articulating ideas and in facilitating a better understanding of the problem at hand. The conception of design as an active co-operative process raises important issues for technologists seeking to support its early phase. In particular, the generation and display of design alternatives is significant for design creativity. The explicit representation of design knowledge is central to this endeavour.

This chapter explores the development in the application of shape grammars to this problem, in particular, advantage is taken of their generative nature in order to produce new design ideas. In the prototype system P1, a designer may interact, guide and select the spatial arrangements generated through interaction with the grammar. Preliminary investigations with designers have led to some understandings about the design search strategies that they employ when using such a system. The chapter concludes by speculating on the potential of strategic knowledge developments that are implied by this research.

7.3 P1 – An Experimental Prototype

An experimental system was developed in order to investigate the utility of a shape grammar as a mechanism for the generation of alternative solutions. In particular, the production of spatial relationships associated with the combination of simple abstract shapes. Furthermore, the prototype enabled discussions to be held with a number of design practitioners concerning the utility of the approach. A basic shape grammar, as defined by Knight (1999), was implemented using LPA MacProlog32 (Johns, 1994). This particular implementation of Prolog was selected specifically because of it graphical capabilities. Furthermore, although developed on a desktop machine, the ability to transfer the source code and run the prototypes on a laptop with relatively little change being required was another positive aspect of using LPA MacProlog as a development environment. This enabled their demonstration to take place in the workplaces of the design practitioners who took part in the evaluation process.

The grammar comprised rules that describe the spatial relationships between a square and a rectangle. The rules are both additive and recursive as the shapes added coincide with those on the left-hand side of other rules in the grammar. This provided the potential for the rules to be re-applied any number of times.

7.3.1 The Role and Operation of Spatial Labels

The prototype P1 incorporated the concept of spatial labels (Knight, 1994). These labels have the effect of reducing the symmetries of shapes to order one (i.e. no lines of symmetry). For example, the application of a label to the bottom left hand corner of a square, usually represented as a black dot, would destroy the object's symmetry (see Figure 7.1).

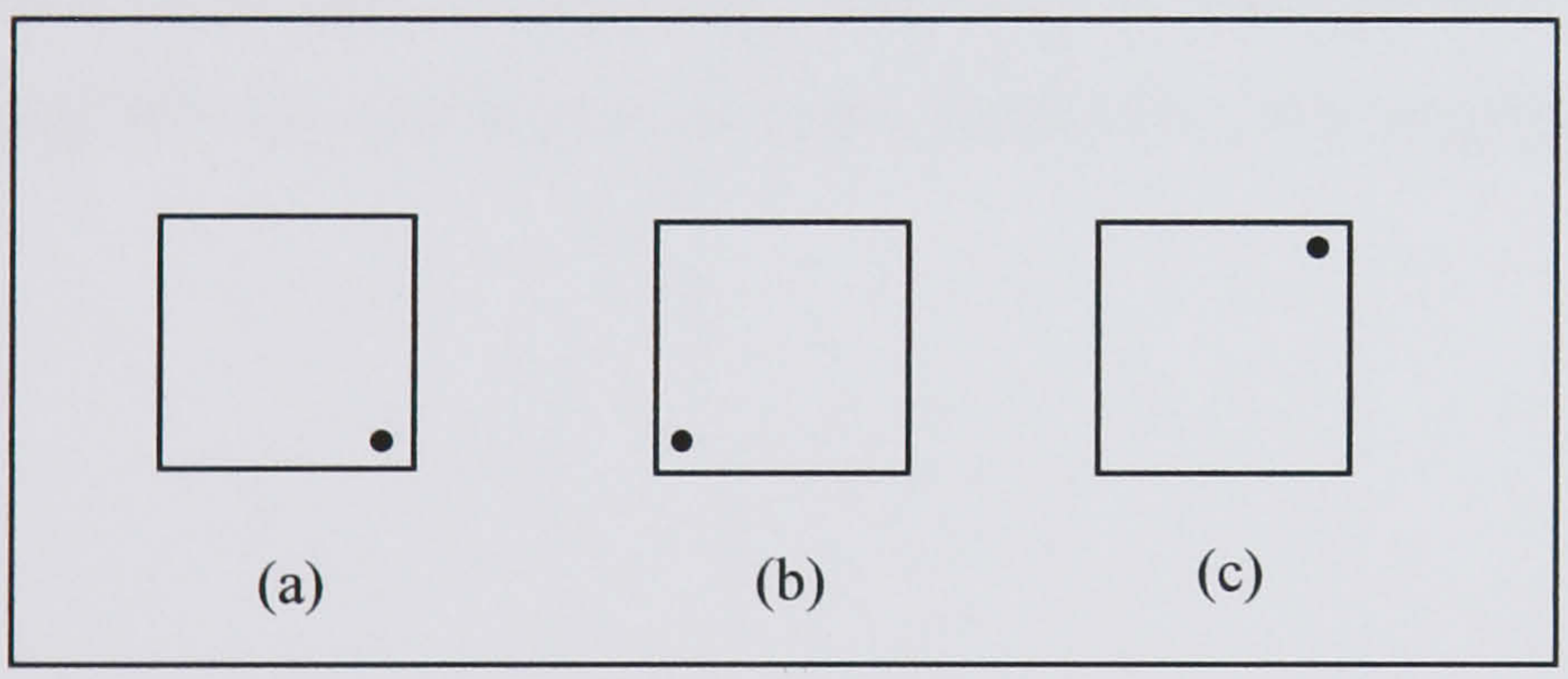


Figure 7.1 (a) Seed Shape (b) Rotation 90° clockwise (c) Rotation 270° clockwise

In Figure 7.1 basic rotations about the centre point are performed on a square which contains a spatial label in the bottom right hand corner, resulting in shapes 7.1(b) and 7.1(c) which are different from the original. If the seed shape had no label, the transformations would have produced no apparent change to the original.

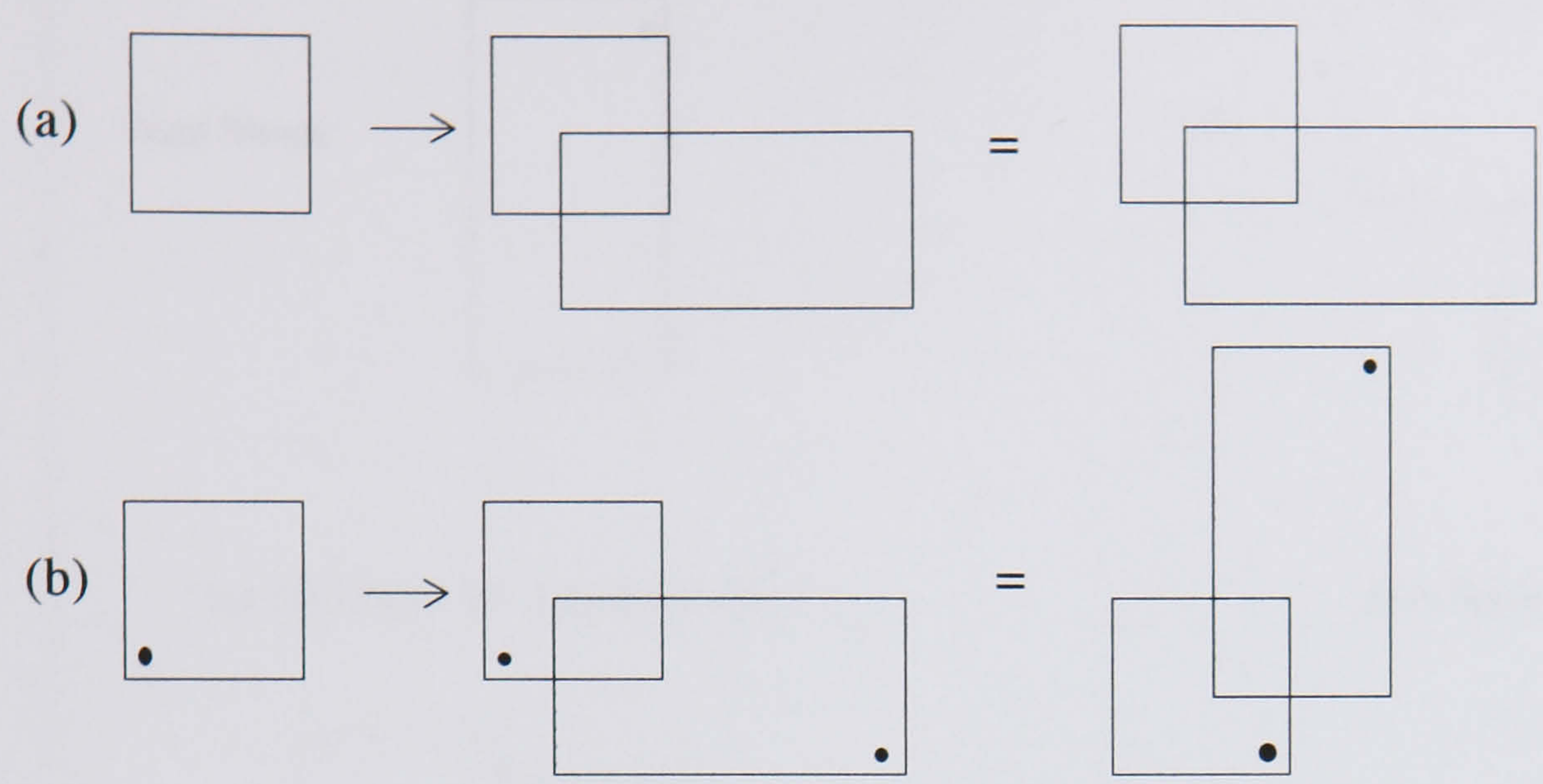


Figure 7.2 Example application of Rule 1 (a) without labels and (b) with labels, in both cases the seed shape is a square, but in (b) it has a label in the bottom right hand corner.

The concept of spatial labels is extended in Figure 7.2. In these cases a rule from the grammar is applied to a seed shape. Figure 7.2(a) illustrates how an unlabelled rule would apply, whereas Figure 7.2(b) presents a rule which uses spatial labels and therefore requires a 90° clockwise rotation of the seed shape in order that it matches the shape on the left hand side of the rule. The rule is then applied and the resulting configuration is rotated 90° anti clockwise in order to return to its original orientation.

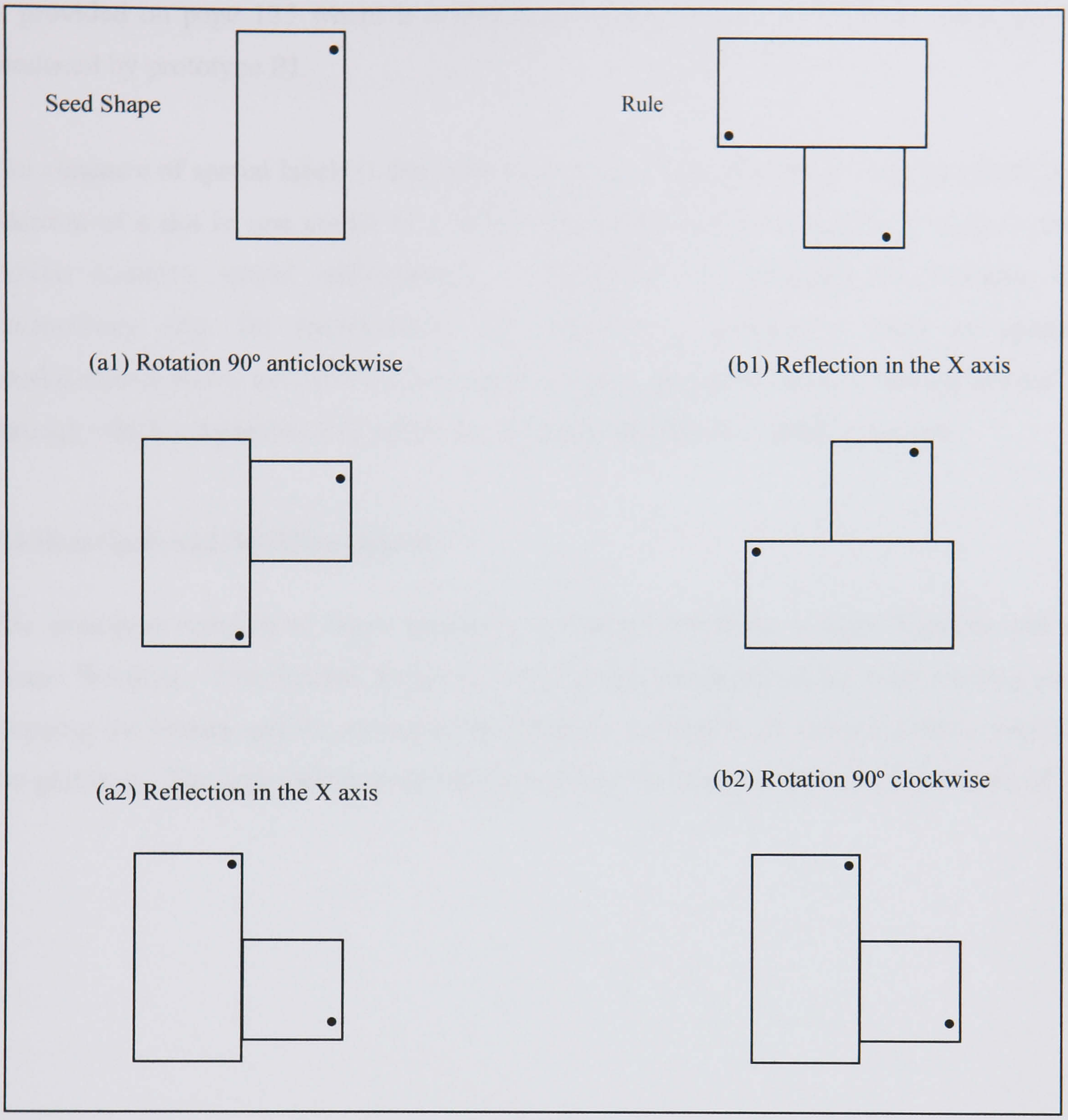


Figure 7.3 Illustration of a combination of Rotation and Reflection in the application of a shape rule

Figure 7.3 illustrates a more complex use of spatial labels. In this case a combination of rotation and reflection is required before the seed shape can be transformed to match the left-hand side of the rule. In Figure 7.3(a1) and (a2) a combination of rotation followed by reflection is applied, whereas in (b1) and (b2) the reflection is applied before the rotation. Within the prototype P1 priority was given to rotation over reflection, thus in the examples provided in Figure 7.3 it is (a1) and (a2) that illustrate how the prototype would actually apply the rule in this case. A more detailed description of rule operation is provided on page 135 where it is described in the context of a shape configuration produced by prototype P1.

The elegance of spatial labels is that with a relatively simple addition to the grammar, the addition of a dot in one corner of a shape, the result is the production of designs that exhibit complex spatial relationships. Furthermore, by allowing the designer to interactively alter the combinations the effect is to generate a range of spatial configurations associated with the grammar. In short, the labels act as a 'meta-grammar' through which a designer can explore the solution potential of a shape grammar.

7.4 Description of the Prototype P1

The prototype consists of three windows: a Control Window, a Rule Window and a Shape Window. The Control Window provides the functionality for both starting and stopping the system and for setting up the labels associated with the rules that comprise the grammar. The application of the labels provides the designer with a special form of

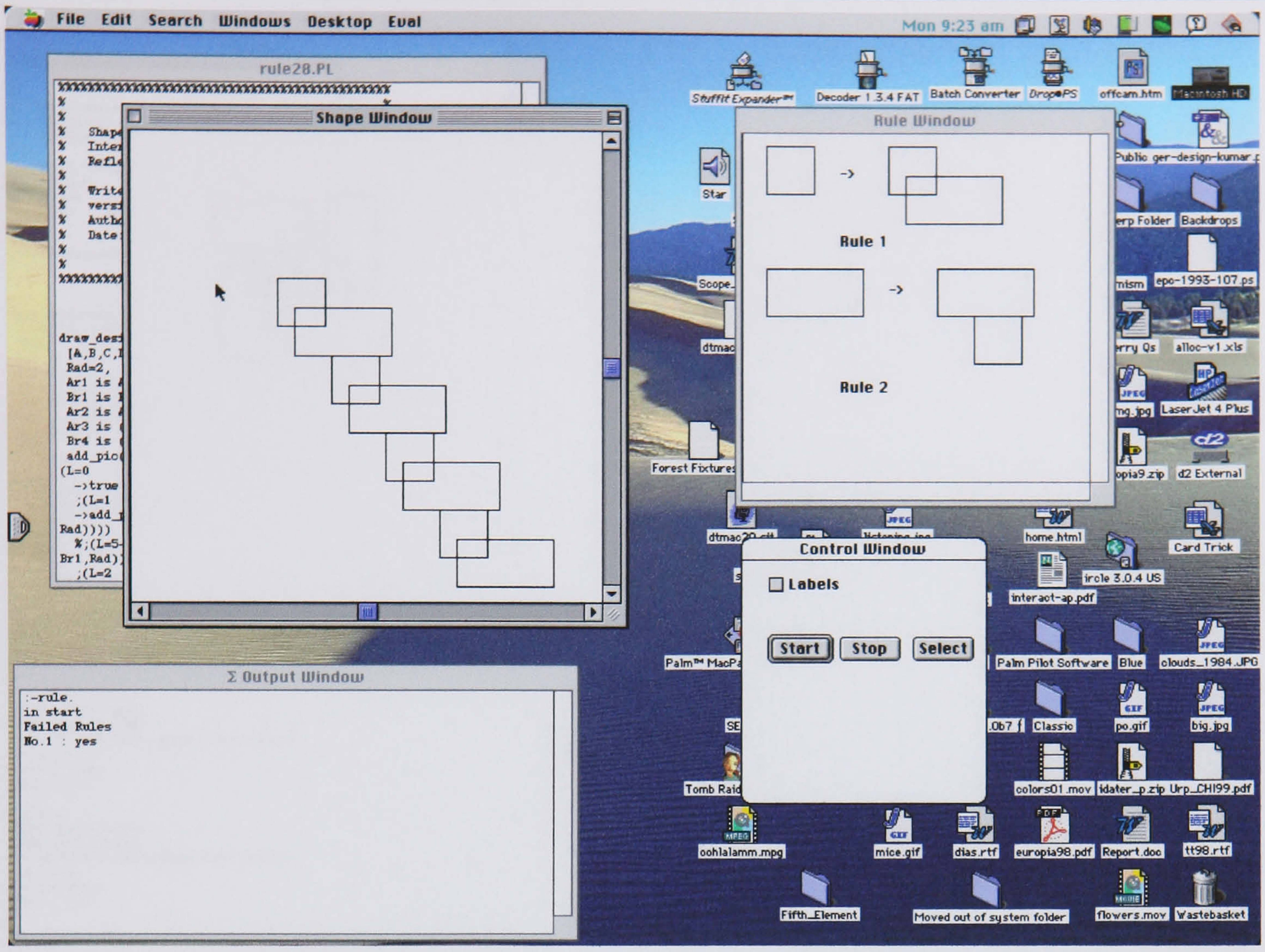


Figure 7.4 Spatial configuration generated by unlabelled rules

'meta-grammar' through which they were able to instigate strategic action on the problem. The rules are displayed in the Rule Window. Initially these are presented without labels, but if the check box in the Control Window is activated the effect is to annotate the rule shapes with a series of small circles located in the corners of each shape. At this point the designer is able to select any combination of labels using the mouse. Selection is indicated by the label turning into a black dot. Once the labels have been set to the satisfaction of the designer the grammar can be started from the Control Window. As labels destroy the symmetry associated with the rule shapes, this necessitated the use of certain transformations, in particular combinations of rotation and reflection, in order that the appropriate rule might first be identified, and then applied to the spatial configuration under development. In effect the designer is exploring the strategies offered by the rules from which to have alternatives generated. The resulting spatial configuration was displayed in the shape window.

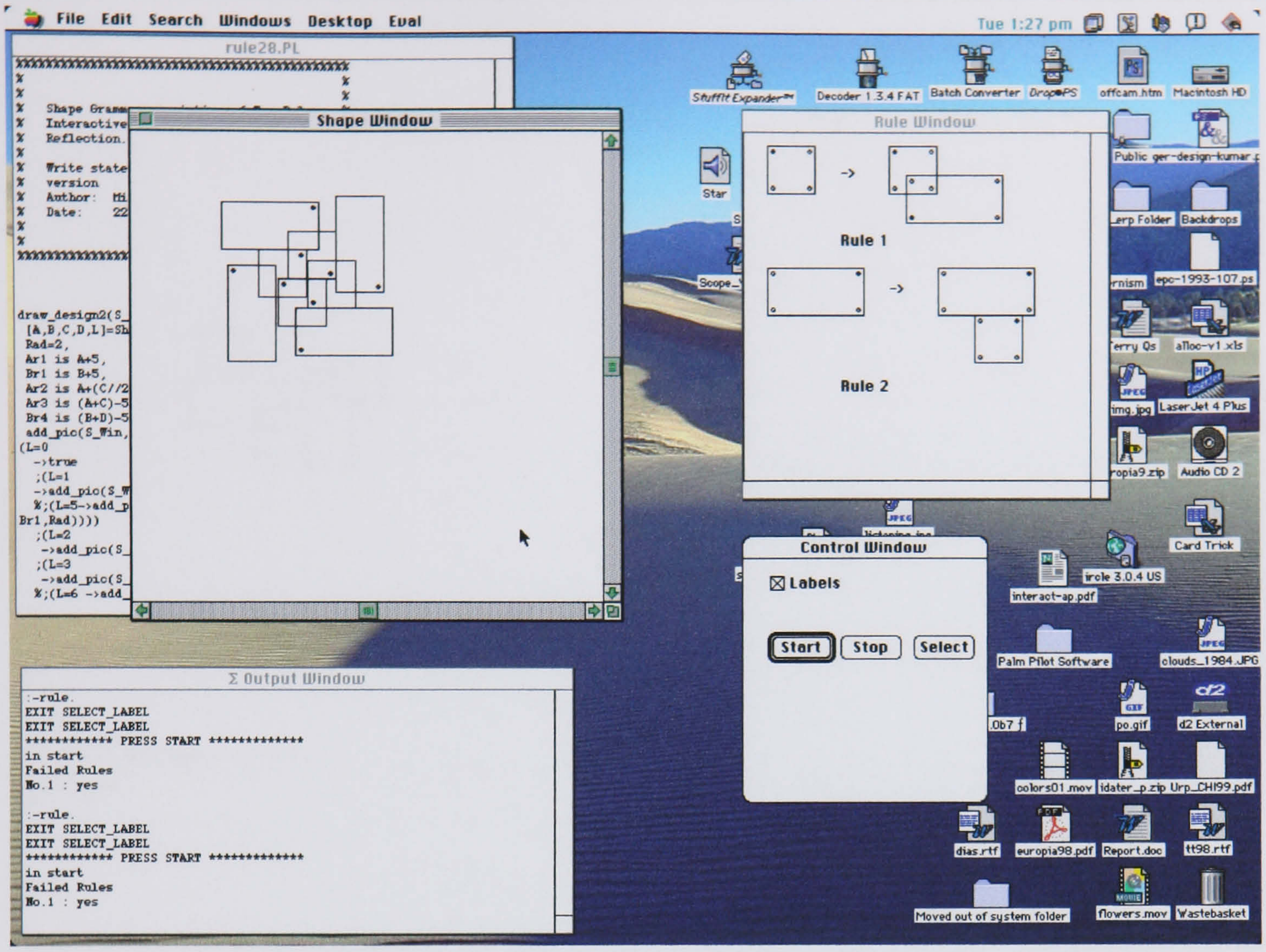


Figure 7.5(a) Example of possible spatial configurations generated through the use of labels.

The action of the grammar is as follows: an initial shape or 'seed' is generated, in this case the shape on the left hand side of the first rule of the grammar. Each rule is then applied in turn until a match was found with the shape added by the previous rule. An example of such a sequence using unlabelled rules is provided in Figure 7.4. Owing to the potentially infinite recursive nature of the rules used in the system each of the sequences was stopped at a particular point, in practice at a depth of seven. If the designer wishes to use labels then the process can be repeated for different combinations of labels, thereby enabling the exploration of a range of spatial relationships. Examples of possible design alternatives produced in this way are provided in Figure 7.5(a & b).

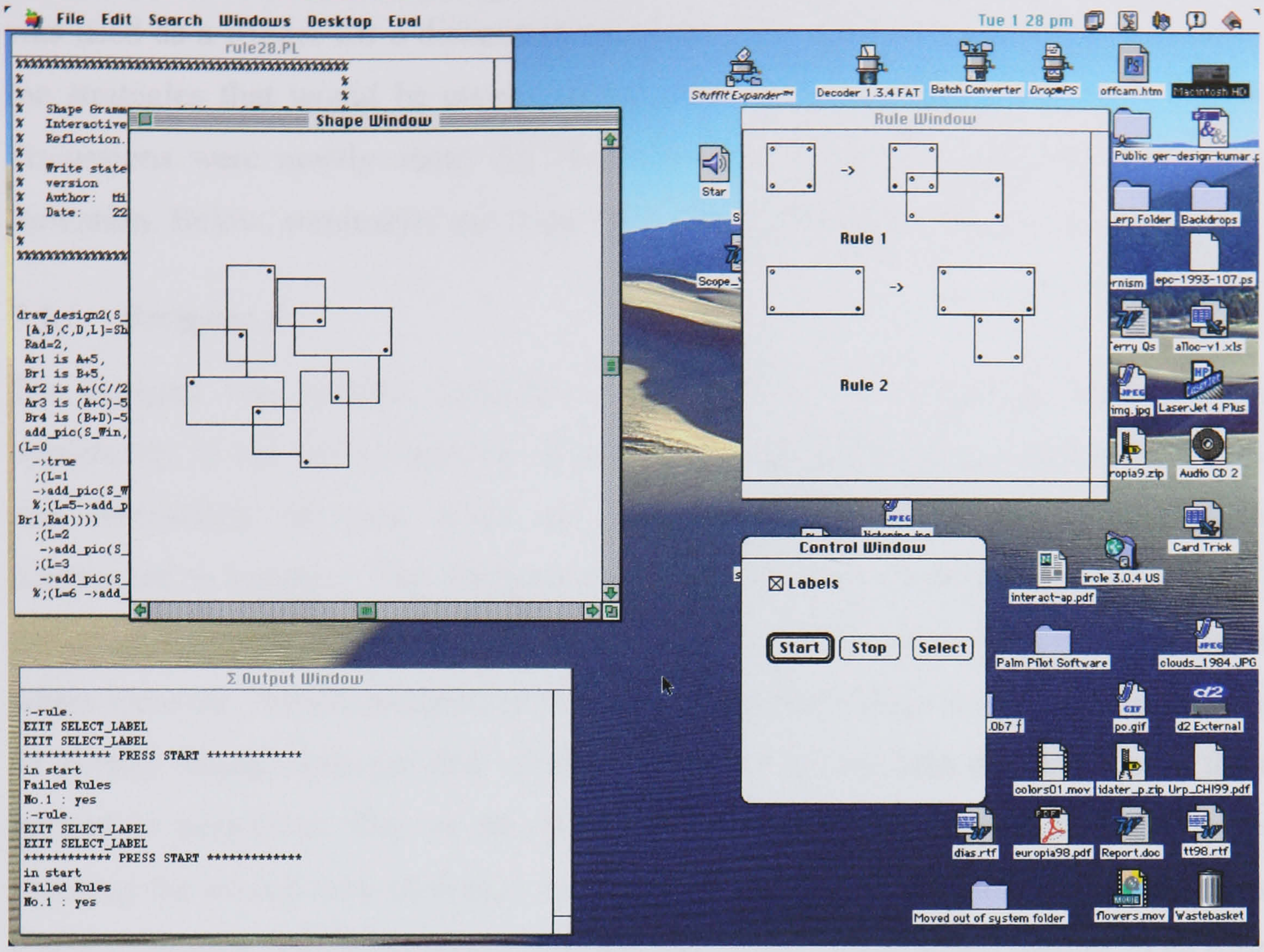


Figure 7.5(b) Example of possible spatial configurations generated through the use of labels.

7.5 Empirical Evidence

The prototype system was used to initiate discussions with three design practitioners. The designers are employed as interior architects in national and international practices with offices in Edinburgh. The strategy of employing professional designers to comment on the prototype complemented the use of students in the earlier studies. As was the case in the earlier studies an interview approach was adopted. These were conducted in the workplace of the designers with the intention of minimising the disruption to their work. In each case, after a short orientation interview, the main interviews ranged from 45-90 minutes and the discussions were recorded using video. At the outset of each interview the prototype P1 was demonstrated using a laptop computer. The structure of the interview was partly driven by the designers' responses to the demonstration of P1 which was used as a trigger for a discussion about the potential of the approach in design and the strategies that would be employed in using it. Interestingly, it transpired that the discussions were mostly about the strategic thinking of the designers during concept formation. Below, summaries are presented of the discussions with each designer.

7.5.1 Designer A

The designer was positive concerning the possibility of technology that offered the opportunity to aid lateral thinking. Indeed, it was described as an ideal scenario. This was particularly the case when the approach provided the chance of something unexpected to happen. The designer commented that he could not decide whether the prototype was aimed particularly at the early conceptual phase of the design process, where ideas are 'thrown around', or if it could also offer a diagrammatic representation of an already thought through idea. If the latter was true, the plan drawings could then be viewed in projection. One of the points that the designer stressed was the issue of breaking the normal way of design working. He talked of the intuitive process of design where influences can be numerous, for example, shape, material and texture. The support prototype only considered one of these.

The prototype itself was considered to be very 'flat' (i.e. 2D) and dealing only in shape relationships. To make such a device more appealing to designers he thought that it would be more appropriate to work in terms of *spatial* relationships (i.e. 3D). He further commented that such a 3D shape grammar would present the design community with something more immediate. The designer commented on a software application with which he was familiar which used the idea of 'meta clay' thereby allowing the designer to mould and shape models of artefacts. In this context he talked of future technology which might enable a designer to 'fashioning things in space'. This comment was interesting because it echoed the importance of the haptic quality of objects, which was identified during the case studies reported in Chapter 5.

The interview was concluded with the designer commenting on how he saw such technology, as exemplified by prototype P1, contributing to the design process. The prototype was viewed as offering 'routes through' the design problem space. In particular, the designer considered it to have the potential to both increase the number of routes considered and to speed up the generation and selection process. This was viewed as assisting with judgements or possible design alternatives. Finally the idea of the organic generation of spatial relationships was raised as a possible direction in which the prototype could be developed. This was prompted by the rectilinear nature of the shapes that comprised the rules embodied in prototype P1.

7.5.2 Designer B

During the course of the interview the designer commented that she felt that shape and space were inextricably linked. The designer stated that during the process of working with shape she was continually thinking about the possibility of space within the shape. This position would appear to support the linkage between shape (2D) and space (3D) an issue that was raised in the interview with Designer A. The designer considered that the prototype and the ideas underpinning it would be relevant to both architecture and interior design.

Later in the conversation the topic of emergence arose and how shape grammars might be applied to shapes that emerge out of the evolving spatial relationships. At this point the issue of and relationships between shape, colour and space arose. In particular the designer commented that in many cases colour could be more visually stimulating than shape and she asked whether grammars of colour, as well as those of shape, could be generated. She continued to argue that such grammars could be used in conjunction with the notion of 3D space, thereby providing a direct linkage of shape, colour and space. In turn this might lead to the formation of a model which reflected the various formats of shapes. This she felt would be very interesting as a conceptual tool with which to think about problems.

7.5.3 Designer C

An initial comment made by the designer, after seeing the shape grammar prototype and in particular the idea of labels, was to ask if it were possible to activate two labels in the one shape which comprised a given rule. He felt this would be particularly interesting as it would introduce a decision point during the application of the grammar. He considered that such points act as a focus of creative thought on the part of the designer even though the decisions made sometimes only exhibited a benefit later in the design process. The designer commented on the similarity to the situation when an extra constraint is added to a problem in order to overcome the 'blank page' and in some way facilitate the design process.

The designer was asked how he thought about space during the early part of a project and in particular whether the shape grammar system struck any chords with that process. He replied that he thought of space in the context of function and also its interaction with other spaces, both internal and external. He felt that the prototype would be particularly useful for massing, which was described as a wilful division of space within a structure. In particular, the ability of the designer to set up relationships, sequences and orders and then to observe what this creates and the possible ideas that could then be hung on the resulting configurations.

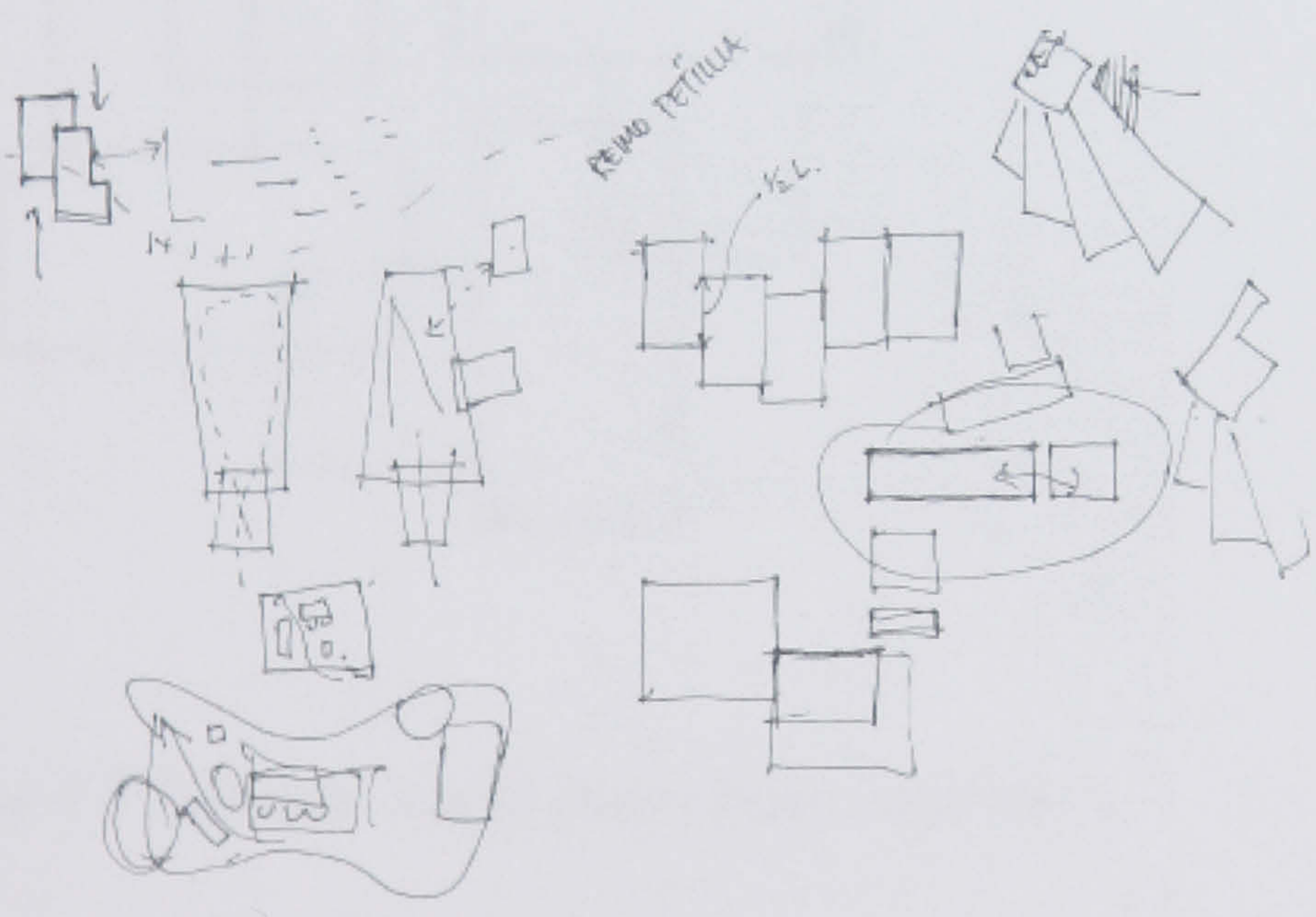


Figure 7.6 Sketch produced by the designer while articulating the idea of irregularity within spatial configurations.

The system was likened to a style of Scandinavian architecture which was based around 'loose fit' rules. The designer described these rules as producing a geometric sequence that acts as a spine or core that gives an order and a legibility to the design. The building functions can then be slotted into the basic structure. In the context of shape grammars, the designer suggested the following possible loose fit rule: a rule such that the placement of the adjacent shape must have a common boundary of at least a certain length. The designer described this as a desire to introduce a sense of irregularity as he considered the highly regular nature of the prototype grammar to be slightly disconcerting. Throughout this part of the discussion the designer was sketching. Interestingly this activity appeared to act as both a means of exploring the issues for the designer and a mechanism for explaining his thoughts to the author. The sketch is presented in Figure 7.6. The regular nature of the shapes also produced the tendency to view the output of the grammar as a building plan. For example, by masking off parts of a given spatial configuration produced by the grammar (Figure 7.7) the designer felt that the output was reminiscent of

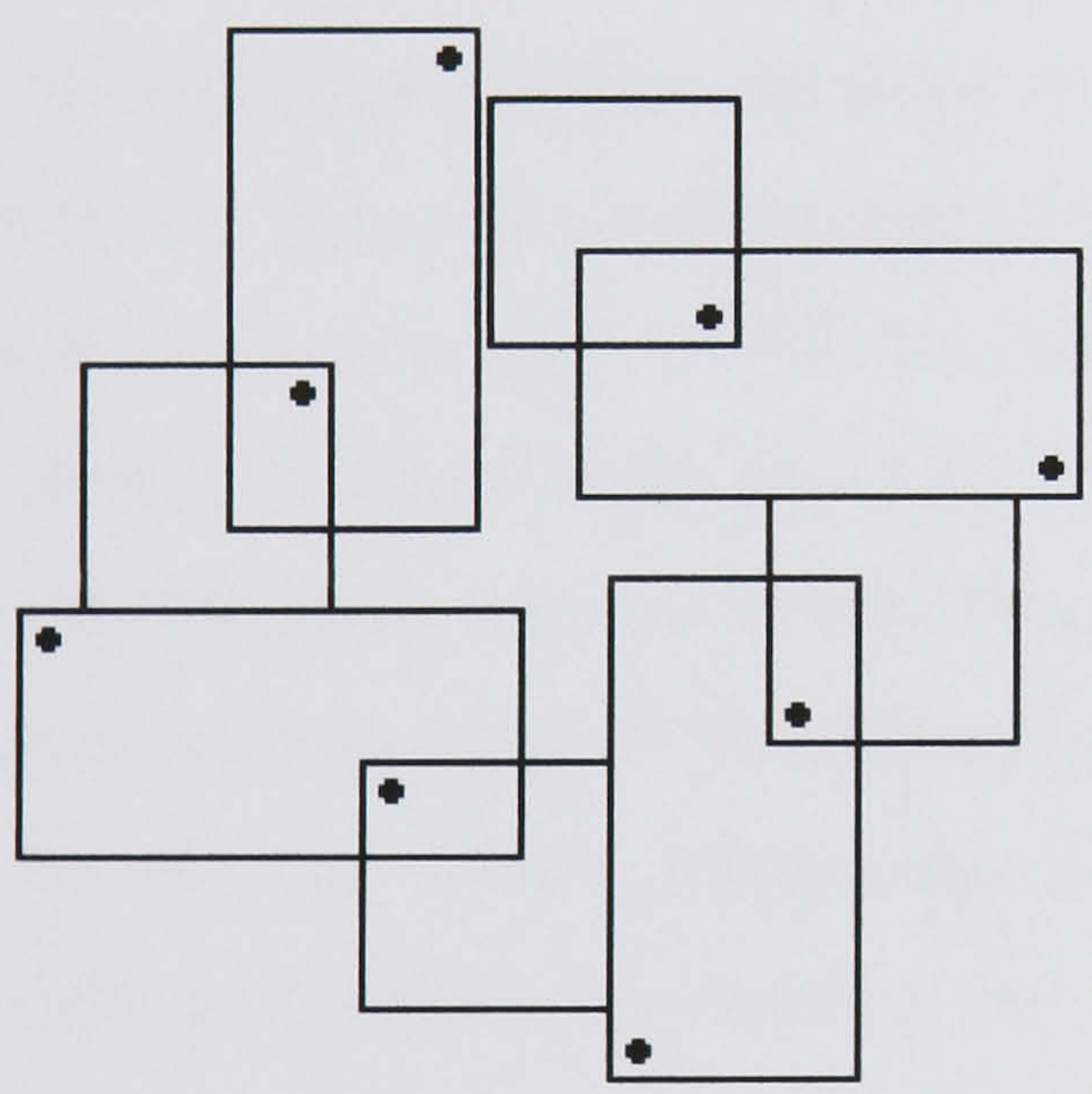


Figure 7.7 Example output from Shape Grammar

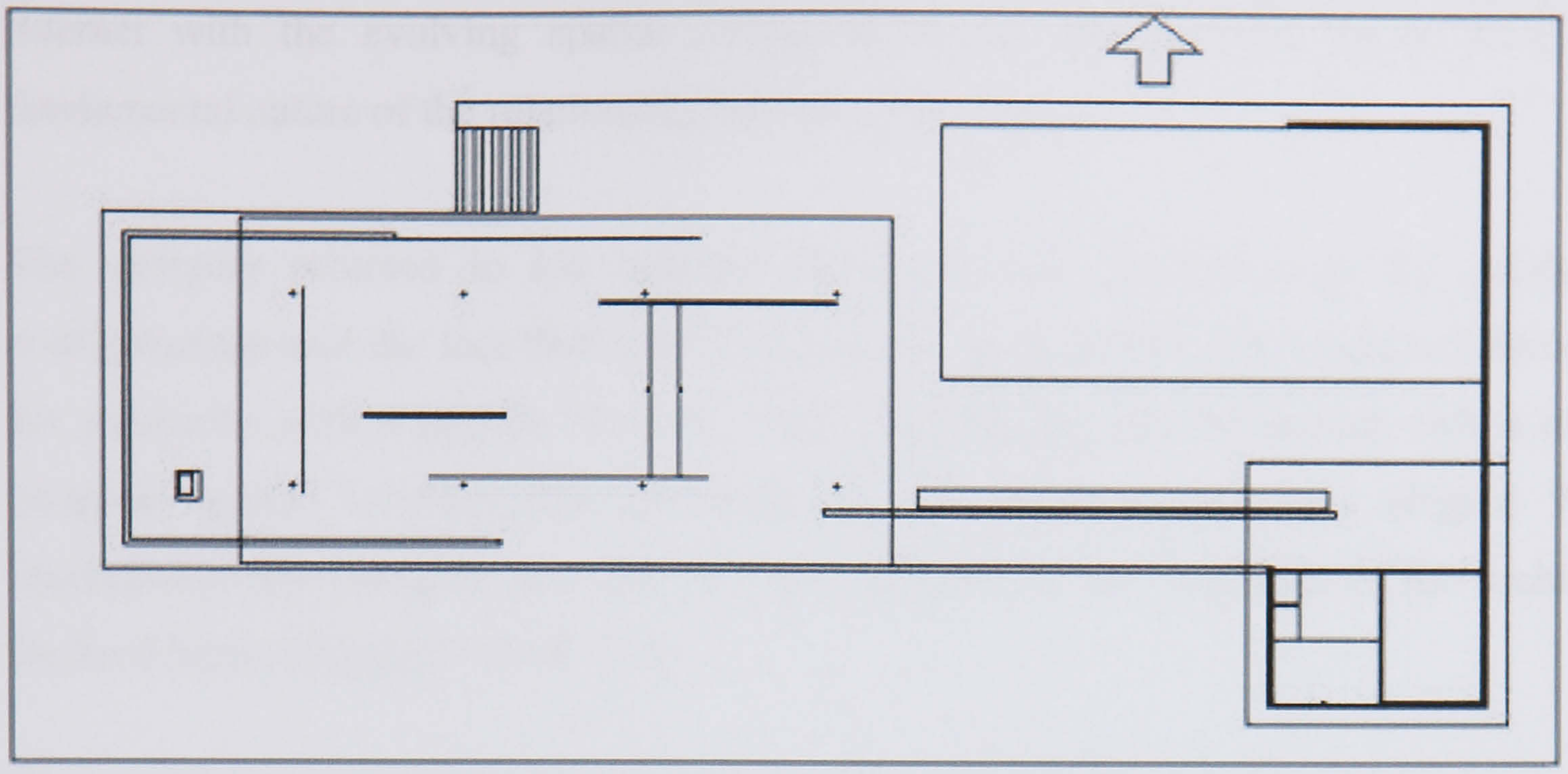


Figure 7.8 Plan of the Barcelona Pavilion by Mies van der Rohn

Mies van der Rohn's Barcelona Pavilion (Figure 7.8). A building that focused upon the overlap between highly structured spatial relationships.

The designer was asked to comment on the previous suggestions to include a 3D quality in terms of how the configurations produced by the grammar were presented. The designer felt that this would be unnecessary as it could make the system more prescriptive in terms of its description of space and deflect the designer away from the more fundamental interaction with the grammar, (i.e. the manipulation of the rules). This comment echoes those of the architect quoted in Cuff (1991) when they talked about the benefits of early 'loose' sketches being non-specific. Thus, in the view of the designer, the addition of a third dimension to the shapes would result in a hindrance to creativity.

At a personal level the designer expressed a preference for buildings comprising more irregular shapes than those produced by the particular grammar employed. He considered that people's perceptions of such spaces is more enduring as such buildings are more provocative and the individual's views are ever changing when interacting with such spaces. The designer suggested that it would be interesting to use the prototype system to explore the nature of just one or two shapes by changing and bending them. The idea was discussed of enabling the designer to deform the rules in some way, then observe and interact with the evolving spatial configuration and thereby learn more about the fundamental nature of the relationship between the shapes.

The designer returned to his concern about the lack of variety in the produced configurations and the fact that repetition may not be enduring. He suggested the need for regularity with a chance element. The designer was then presented with a more irregular spatial configuration produced by the prototype grammar (Figure 7.9). Immediately the designer saw this he was reminded of the buildings of the architect Richard Meier (Figures 7.10 & 7.11).

The designer considered that the idea of introducing a degree of change in the application of a rule would produce more irregular and therefore interesting shapes. For example, a geometric shift could be incorporated in the relationship after each successive application of the rule. The designer considered that an interesting feature of the prototype was the way in which it made a designer consider the process of evaluating a space. Indeed, the designer commented that it would appear to be the sole purpose of some architects to produce repetitive progression of a shape. For example, the way certain housing projects interconnect and follow the contours of the land, the designer considered these to be an imposed order rather than a natural one. Continuing the housing theme the designer commented that again some of the patterns produced by the grammar were reminiscent of 1970s local authority housing plans, in particular courtyard housing, (see Figure 7.7).

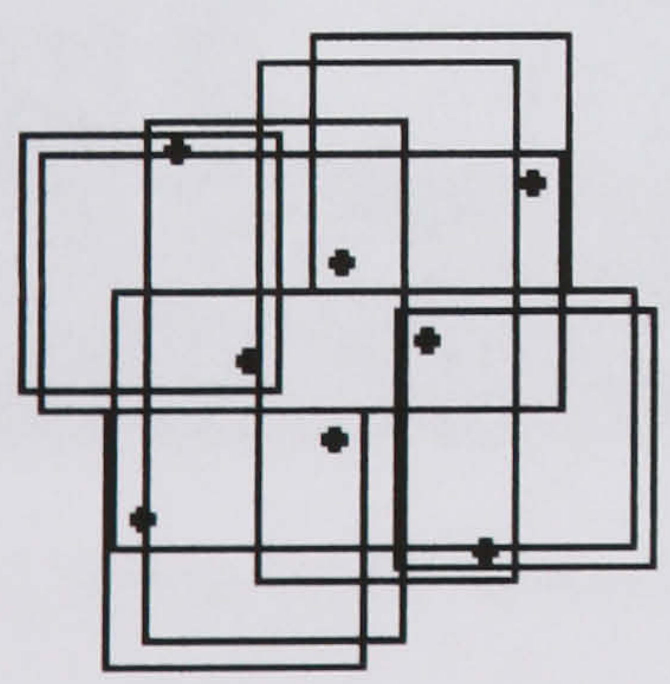


Figure 7.9 Output from Shape Grammar system

In the view of the designer the major benefit of a grammar based system was to enable the exploration of a small number of shapes with a small number of rules. Rather than pure repetition of shape this would enable the designer to exercise a great deal of issues in terms of the relationships between the shapes. If the rules were chosen with a balance in mind then it could be expected that the resulting configurations would also exhibit a similar degree of balance. Indeed the progressions that might be generated would express so much more about the initial spatial relationship. This would be the same for both regular and irregular shapes. In the words of the designer,

> 'if the rules are "right", then the subsequent combinations will also be "right".'

The conversation moved on to the idea of emergence and the way that shapes can appear through the combinations of others. The designer questioned the merit of such an approach from a spatial point of view and commented that emergence appeared to run contrary to the fundamental structure of shape grammars. He suggested that it would be more logical to:

> 'apply something that you think would be useful in the first place rather than waiting for something to fall out by chance.'

Figure 7.10 Hartford Seminary, Hartford, Connecticut, USA by Richard Meier (1978-81)

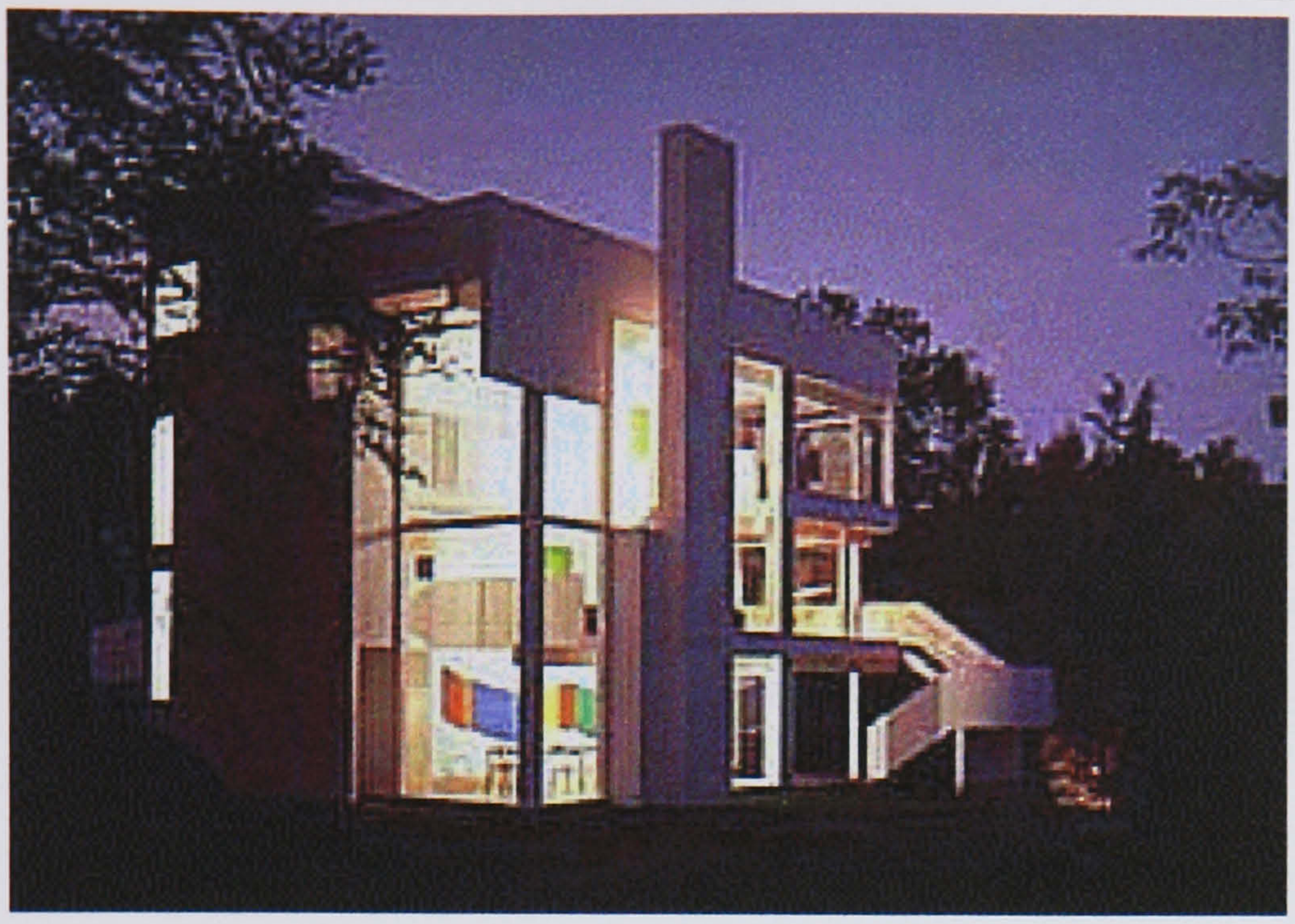


Figure 7.11 Smith House, Darien, Connecticut, USA by Richard Meier (1965-67)

The notion of loose fit rules arose again, in particular, the progressions that might be generated - spines and cores. The designer commented on architects' designs in which clusters of objects, say houses or rooms, were broken by other objects. The

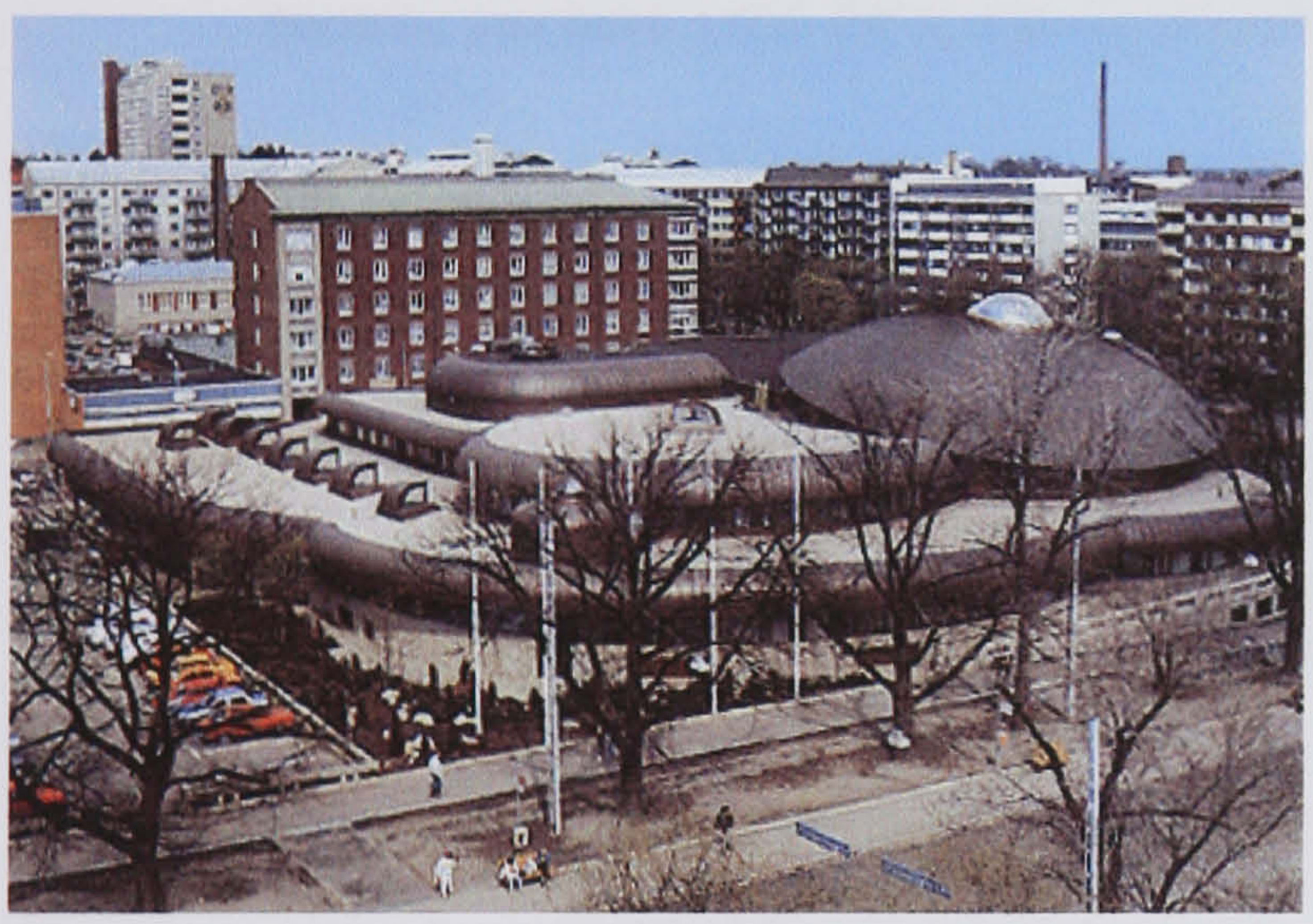


Figure 7.12 Tampere Library - view from the air and frontal elevation, Reima Pietila.

designer said that he suspected that the architect was using implicit 'rules' to create these structures. The idea of a repeated mutated shape reminded the designer of Reima Pietila's library building in the shape of a fan (Figure 7.12). The introduction of such rules would contribute to the production of more organic configurations. The designer commented that maybe designers are always using rules in some way. For example, maybe these take the form of having a tendency to behave in a particular way to the extreme of something that they would never do. Classical architecture consisted of a series of rules and the buildings that were produced are highly thought of.

The interview concluded with a comment from the designer. It is included here because it offers a salutary reminder that ultimately design is concerned with the creation of artefacts:

> 'one of the most important things that architects and designers have to learn is the ability to compensate for the way that they have to depict things.... if you give modelling materials they never build it in the way that they would draw or design it because you have a feel for it, a sense of scale. Drawings are always going to kid you.'

7.5.4 Key Issues

The benefits of shape grammar based support systems were seen to come from various ways in which they could focus creative thought:

- show the implications of specified relationships;
- encourage the evaluation process;
- force creative decision points;
- encourage lateral thinking.

7.6 Conclusions

Based on the research reported the following conclusions were made:

- shape grammars successfully provide a mechanism for expanding available design strategies;
- alternative designs, in the form of spatial configurations, encouraged design exploration of the implications of using a particular rule set.

7.7 Discussion

Shape grammars provide a formalism in which rules about shape arrangements can be specified together with a mechanism with which it is possible to automatically generate new conforming arrangements. As the prototype system demonstrates, such a system can use graphical representations (based on the shapes themselves) for the user to see and manipulate. The rules of a shape grammar used in this way represent one aspect of design knowledge and the system prototyped is an example of one that allows the designer to interact with that knowledge in a domain specific way (Edmonds and Candy, 1996). It would seem that shape grammars do have a role in this process.

Amongst the proposals that came from the designers was the idea of 'loose fit' rules. This idea implies that the grammar might be specifically directed at core design structures, where perhaps the application of relatively well organised design rules make most sense. In this view, much elaboration is left outside the support system and can be dealt with more intuitively. The suggestions of 'organic generation' may have been made in much the same spirit. Here, diversity is added by what might be thought of as the application of mutants of the rules, such as a small geometric shift at each application. Such a mutation could, of course, come from the application of a 'meta-rule'. If that was the case one could envisage a scenario where designers experimented with the meta-rules in order to understand their impact on the generation of new ideas.

In all cases, a system such as that prototyped can be seen to act as a stimulus to the thinking of the designer. It might offer a range of alternatives that stimulates thinking about the criteria for evaluation. Interaction with it might demand other decisions that also stimulate creative thought. Thinking about the grammar being employed may itself stimulate 'set breaking' or lateral thinking and cause the designer to re-define the rules being employed.

7.8 The Relationship between Prototypes P1 and P0

At this point it is appropriate to reflect on the relationship between prototypes P1 and P0. A period of approximately seven years separated the development of the prototypes. In that time the aim of the research had changed from a study of co-operation as a paradigm for human computer interaction (HCI), to an investigation of computer based support of the early phase of design. Notwithstanding these differences, at both the intellectual and temporal levels, there are themes that permeate the prototypes and also important differences.

The generation of alternative solutions remains a central characteristic of both prototypes, although the method of generation has radically changed. Prototype P0 utilised a set of 'hand crafted' rules based on symmetry and the golden section, while P1 incorporates the concept of shape grammars as the underpinning generative mechanism. The manipulation of rules by the designer so as to create a variety of alternatives was also evident in both prototypes. P0 adopted a goal orientated approach which manifest in the designer being able to explicitly communicate goals, in the form of spatial relationships, to the system. Furthermore, they could also alter the priority of the rules that generated the alternatives. The strategy reflected the emphasis on co-operation. P1 enables the manipulation of rules which comprise the shape grammar through the use of 'change rules', in this case spatial labels. It is contended that while the intent of rule manipulation is present in both P1 and P0, its execution in P1 is more appropriate to the support of design. This raises the most important distinction between P1 and P0, namely the conceptual level at which each prototype operates. P0 was designed to represent a particular design task, that of locating furniture within a floor plan. The rationale behind this decision was to make the instantiation of the concepts of co-operation more tangible and hence accessible. The result was the development of a prototype which was viewed as a system for room layout and which was criticised for the simplicity of its solutions. P1 has deliberately adopted a higher conceptual level, as it focuses on the relationships between basic shapes. As a consequence, interpretation of the resulting configurations was made by the designer and this, it is contended, is a more appropriate level of interaction for a system aimed at supporting the early phase of design. While P0 is distinct from P1, the importance of P0 in shaping the later system's approach to the support of design exploration should not be underestimated.

7.9 Prototype P1 – The Next Step

The proposals of the designers suggested a number of directions for further research into the use of shape grammars to support design. The areas of a 3D shape grammar and a colour grammar will be considered in the concluding chapter of the thesis. The suggestions of the designers concerning possible extensions of the transformation mechanisms contained within the grammar were viewed as more pertinent to the current research. Firstly, the concept of 'loose-fit' rules that can generate, for example, the spine of a building. This approach offers the tantalising opportunity to introduce a level of 'controlled irregularity' into the application of shape grammars. This is a feature which, in the opinion of the designers, would encourage design exploration and hence the potential for creative solutions. Secondly, the related question of organic growth of rules. Two approaches appear fruitful. The first is to add meta-rules that modify the base shape grammar in geometric ways. This could be done using the approach of Ohsuga and Yamauchi (1985). The other approach could be to apply genetic algorithms (Goldberg, 1989) to the rules, rather than to the objects, of design.

Based on this study two main conclusions can be made. Firstly that shape grammars can successfully expand the range of design strategies available to a designer and, secondly, that the provision of computational support for the exploration of the implications of employing rule sets is promising. A number of directions for further research have been identified and it is one of these, the design and implementation of 'loose-fit' rules, that will form the basis of the next chapter of the thesis.

8 Prototype P2 – The Introduction of Loose-fit Rules, Adding to the Uncertainty

8.1 Overview

This chapter will present the following:

- a description of the rationale underpinning the implementation of loose-fit rules;
- a description of the prototype P2;
- a summary of the interviews with design practitioners;
- a statement of the conclusions;
- a discussion of the themes raised by prototype P2.

8.2 Introduction

This chapter will introduce the next version of the prototype system to support design exploration, entitled P2. The prototype contains an implementation of 'loose-fit' rules, as introduced in the previous chapter. A rationale for the inclusion of loose-fit rules is included here, together with a description of the prototype P2. In a similar manner to P1, the prototype P2 was used as a vehicle to discuss issues relating to its support of design. The design professionals who previously had discussed P1 participated in the evaluation of P2. These discussions are presented here, together with conclusions based on the work.

8.3 The Rationale Behind the Implementation of Loose-Fit Rules

Rules in design can be thought of as providing a legibility, particularly when they are used to produce geometric sequences. In the context of a particular style of Scandinavian architecture, one of the designers during the interviews described in the previous chapter commented that it appeared to be based around, what he referred to as, loose-fit rules. He described these as rules that determine the location of objects relative to each other in such a way as to still include a certain randomness in the final solution. Their application provides a spine within which basic building functions can be placed. The rules provided an order, but not one that was apparent to the casual glance.

The shape configurations generated by P1, while clearly thought provoking, did exhibit a high degree of regularity. This fact, it was suggested, could limit their ability to prompt a designer towards viewing a problem in a new light. To address this issue the loose-fit approach will enable a designer to set upper and lower bounds on the application of a particular rule. It is contended, this would have the effect of introducing an unknown element into the rules application. Thus the rule provides an underlying legibility while also including a randomness which operates within a set range. How and where each shape would be placed, within the given bounds, is a question which will be addressed in the remainder of this chapter. The introduction of irregularity in the application of a shape grammar has the potential to generate shape configurations which are more enduring, provocative and ultimately those which could inspire new and novel ways of thinking about the demarcation of space.

From the perspective of research in the field of shape grammars, the proposed loose-fit rule is, in effect, a new instance of the class of change rules. Furthermore, its implementation addresses an important interface issue that was identified during a workshop on shape computation at MIT, namely the visual parameterisation of rules. In his keynote address Gips (1999) quotes Ulrich Flemming's comments concerning this issue, in particular the need for:

> 'A graphical user interface that allows for the graphical definition of parameterised shape rules (a tricky, but intriguing proposition). I would use it to set up a laboratory for the experimentation with and the investigation of architectural forms'

From the perspective of shape grammars, loose-fit rules constitute a new type of change rule. In the context of this research their aims were twofold. Firstly to introduce a 'controlled irregularity' into the generation of shape configurations thereby making them more provocative to the designer and, secondly, to enable the investigation of the technique of parameter visualisation as a means of representation.

8.4 Prototype P2 – An Implementation of Loose-Fit Rules

Central to the concept of loose-fit rules was the provision of a mechanism whereby designers could introduce a level of irregularity into the application of the rules and the consequent shape configuration. The rationale being that such configurations had the potential to be more thought provoking. At the outset two possible loose-fit rules were considered. The first related to the degree of overlap between shapes that comprised the right hand side of a rule. For example, the manipulation of the degree of overlap could enable a designer to explore issues relating to housing density and building configuration. The second approach was to enable a designer to set a maximum and minimum value relating to the relative position of shapes along their adjacent axis. Such a rule offers the designer the capability of creating spines constructed from shapes that while irregular in their configuration still possess an inherent legibility. For example, during consideration of the layout of buildings and their relationship with the geography of the surrounding countryside. Based primarily on the pragmatics of implementation within the software architecture of prototype P1, the decision was taken to implement the second example of a loose fit rule, while the rule relating to density will be returned to in the Future Work section of the final chapter (see Section 9.6.1.2)

The prototype system P2 incorporated the concept of loose-fit rules. Based on the grammar implemented in P1, a third loose-fit rule was added. The right hand side of this rule comprised of a rectangle and an adjacent square. The loose-fit rule was developed to enable the designer to manipulate the spatial relationship between these shapes (see Figure 8.1).

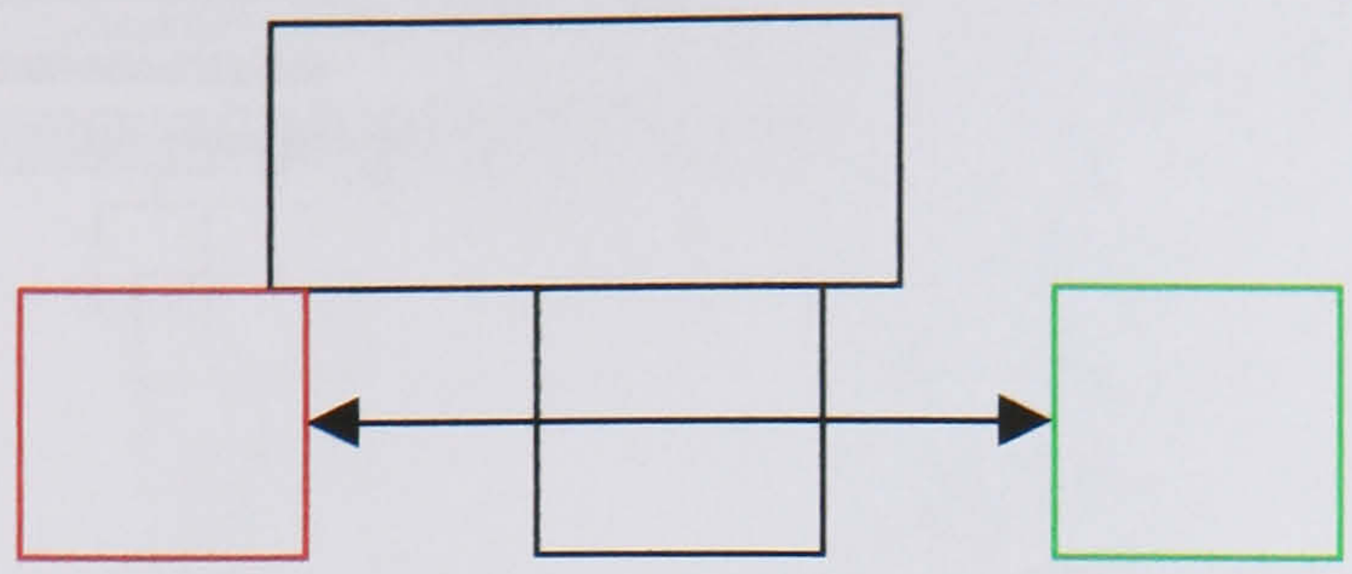


Figure 8.1 Illustration of setting a maximum and minimum bounds on the right hand side of the loose-fit rule, as implemented in prototype P2.

The addition of check boxes in the Control Window allowed the designer to activate certain combinations of the rules that comprised the grammar (see Figure 8.2). In this case activation of Rules 1 and 2 enabled the use of spatial labels, as described in Chapter 7. The activation of Rules 1 & 3 enabled the designer to relax the spatial relationship between the shapes on the right hand side of the rule. If this option was chosen, through the selection of a radio button in the Control Window, a dot appeared in the centre of the shape whose position could be relaxed. In the case of prototype P2, the designer was, by means of the mouse, able to select and move this shape along the X-axis, so as to create a maximum and a minimum position within which the grammar would operate during the application of the rule. These positions were indicated within the Rule Window by drawing the minimum position in red and the maximum position in green, (see Figure 8.2).

The next stage in the set-up of the loose-fit rule was the selection of a method whereby the shape is positioned relative to the maxima and minima. It is this choice that will ultimately determine the degree of uncertainty associated with the application of the rule. At this point in the interaction a series of options are made available to the designer. They have the choice to select either a random application of the rule within the bounds previously set (see Figure 8.2), or an automatically produced sequence or progression. In terms of sequences, the designer could choose from a simple stepped sequence using small, medium or large increments. The increments are predetermined within the software and the application of such sequences result in the placement of the shape

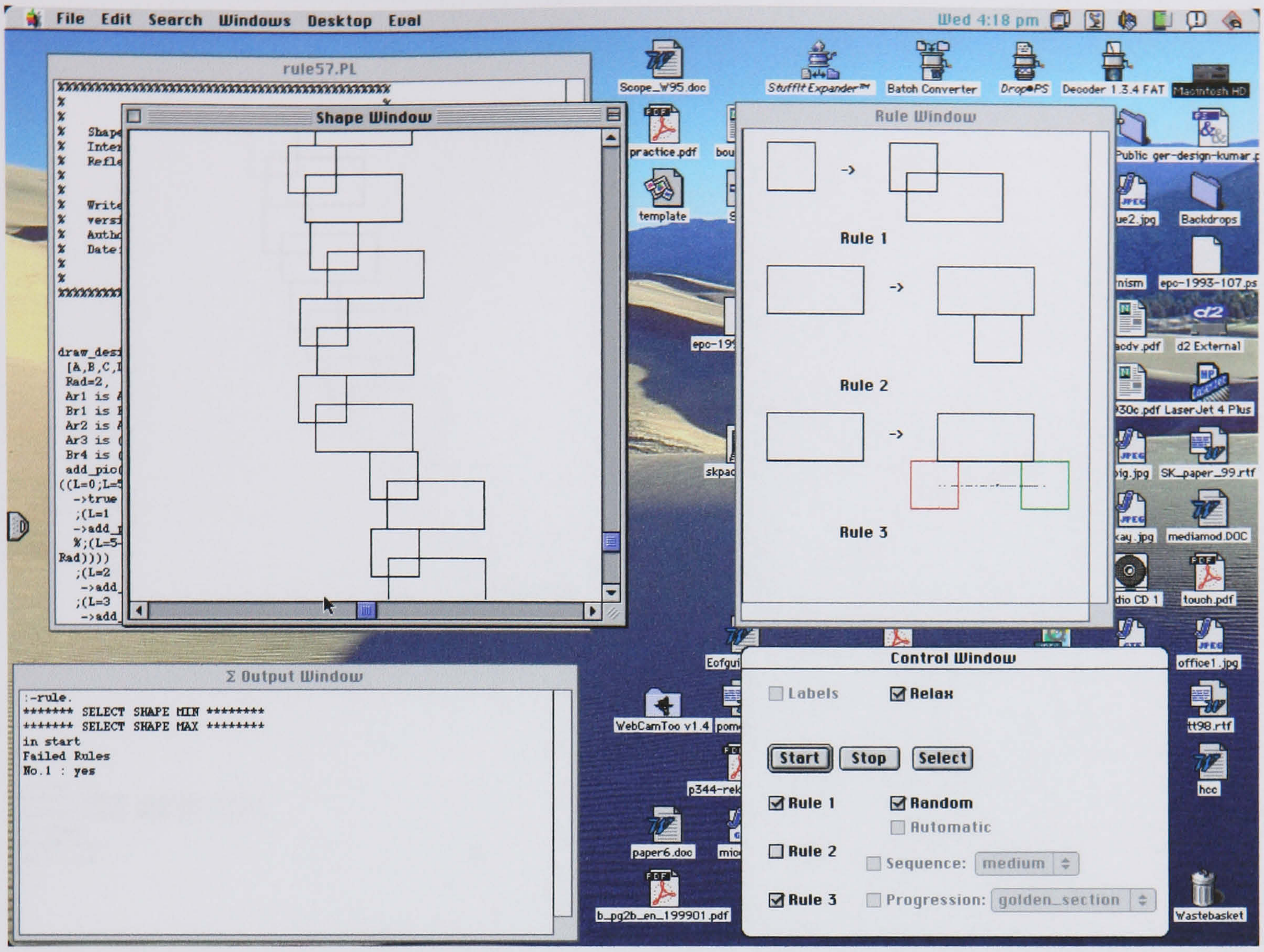


Figure 8.2 Loose-fit rule generating a random placement of shapes

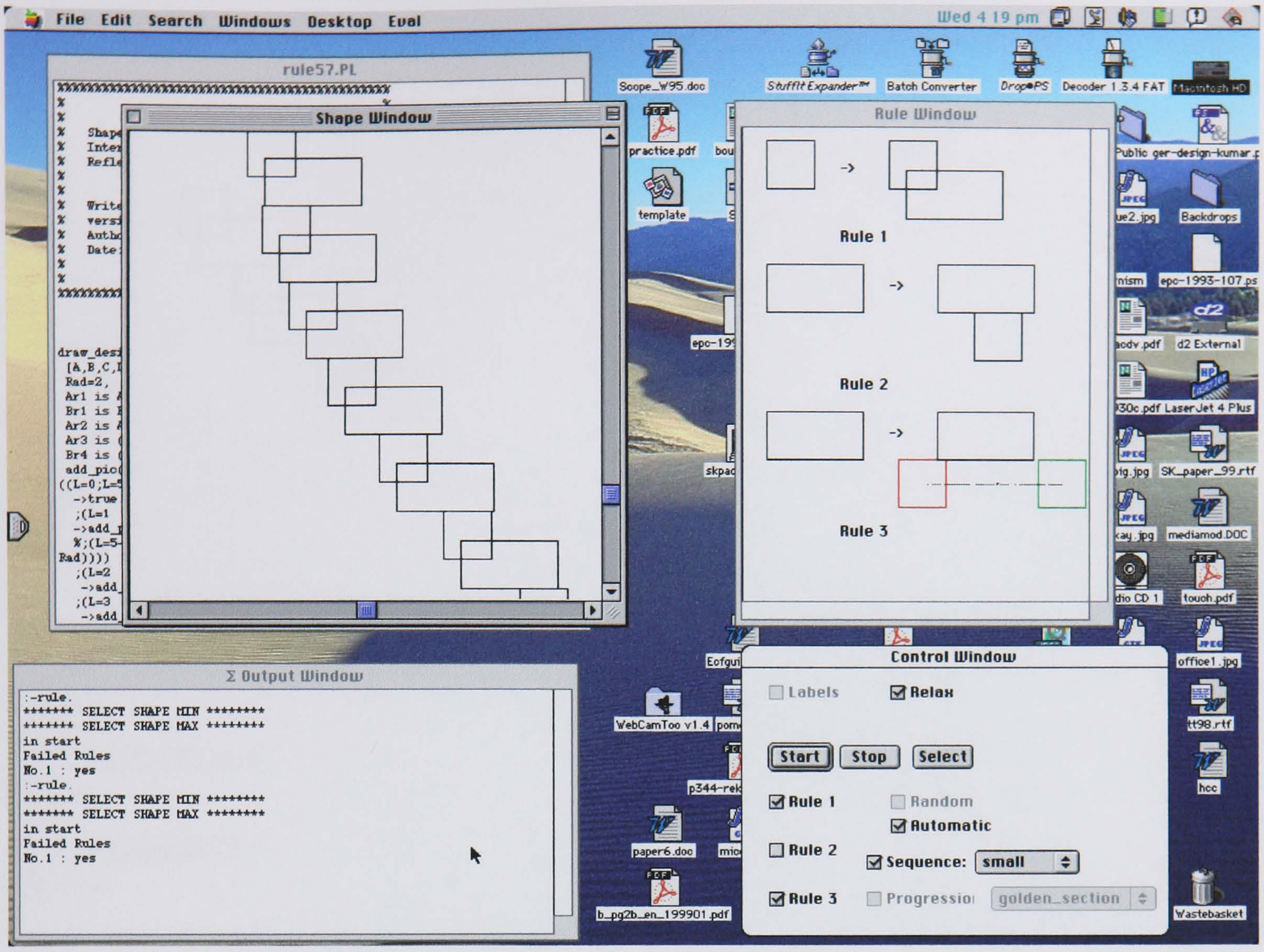


Figure 8.3 Loose-fit rule applying a sequence – small increments

oscillating between the maxima and minima at a rate dependent on the selected increment (see Figure 8.3).

Two progression types are implemented within prototype P2. They are Golden Section and Fibonacci. Figure 8.4 illustrates a sequence of shapes generated using the golden section. These were selected as they offered a recognised way of dividing space and also because of their traditional use within the design community (de Sausmarez, 1964). Primarily they were used to cut down the number of possibilities in compositional tasks by the application of rules to govern the placement of objects in a few initial sketches.

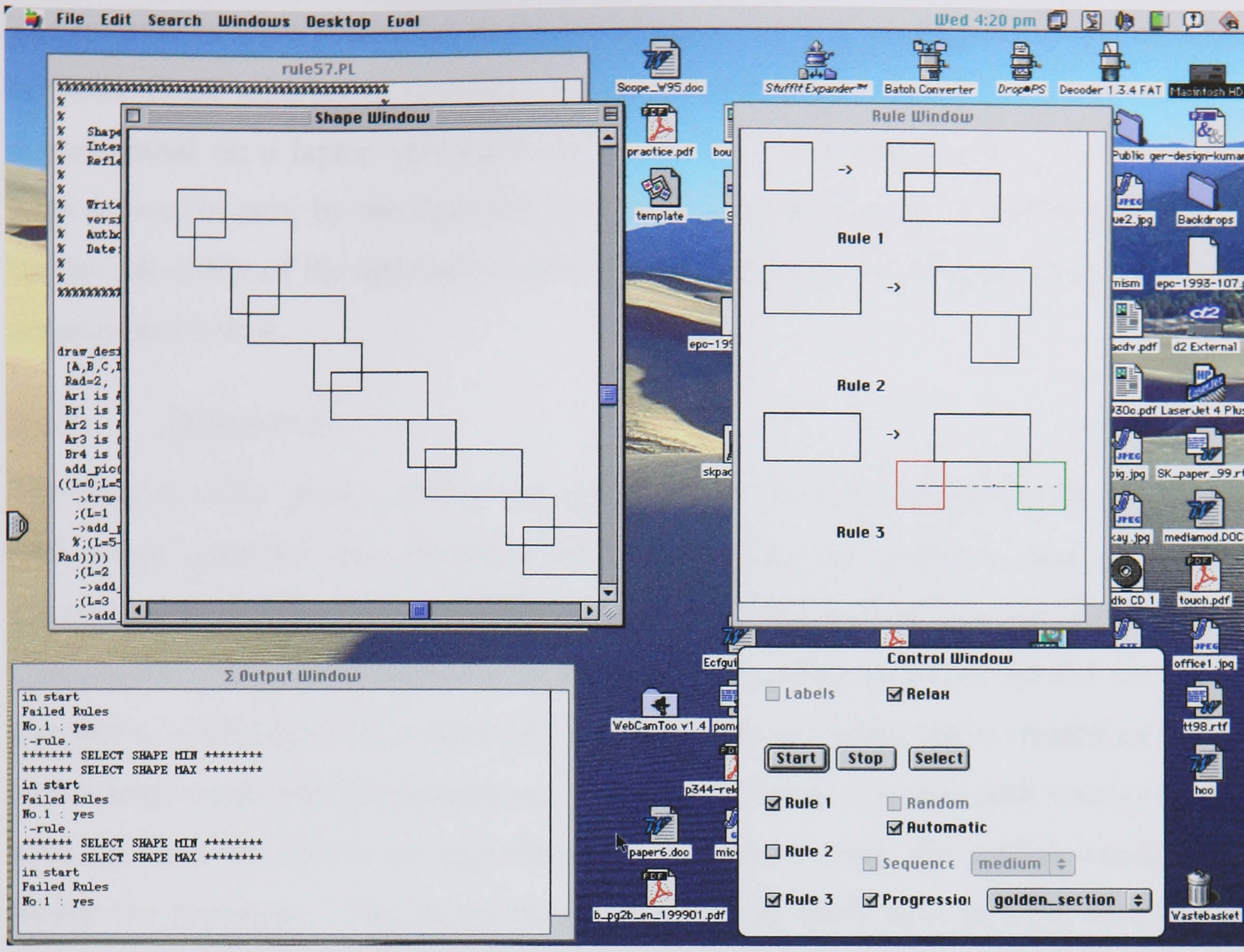


Figure 8.4 Loose-fit rule progression generated by means of the Golden Section

Furthermore the inclusion of the Golden Section echoed its use in the prototype P0 and, as such, offered the author an appealing sense of closure.

The concept of loose-fit, as implemented in the prototype P2, had the effect of generating 'spines'. These were described as providing a legibility to the clustering of objects. For example, during the relative positioning of a series of dwellings within a housing development.

8.5 Empirical Evidence

In a similar manner to the evaluation of prototype P1, P2 acted as a means of orientating discussions with design professionals. Two of the original three designers participated in these discussions. The third designer was unavailable due to long term work commitments. This illustrates one of the problems of working with experts in any field.

The interviews were conducted in the workplaces of the designers and typically ranged between 45-60 minutes in duration. As in the previous evaluation, the software was demonstrated on a laptop computer and the session was videotaped. The discussions were driven, in part, by the designers and were used as a means of gaining leverage on the overall utility of the approach to the support of design. Summaries of the interviews are provided below.

8.5.1 Designer A

The idea of using colour, which was raised in the previous interviews, in conjunction with shape grammar was discussed and in particular the problems that arose when calculating the overlap between shapes as they were added to the evolving configuration. Calculation of the overlap between the current shape and the previous one did not present a problem. Difficulties arose when the placement of the current shape created an overlap with a shape other than the penultimate one. The ability to calculate such overlaps would have required the use of an alternative way of representing the spatial configuration within the prototype. The issues raised here will be dealt with in more detail in the section describing future research areas in the final chapter.

The designer was informed of the major changes that had been made to the system since it was last demonstrated. In particular, the method whereby the physical relationships between the shapes that comprise the right hand side of the rule could be altered by the designer. The behaviour of the loose-fit rule was demonstrated and prompted a discussion concerning the role of constraints within the activity of design. For example, how such rules might be relaxed and how designers seek to generate innovative solutions within such an environment. The designer commented that the use of squares and rectangles in the prototype system had the effect of emphasising a sense of rigidity. The use of curves or more organic shapes were proposed as an alternative.

The designer raised the question of whether the prototype system was viewed as a development tool or a conceptual tool. Furthermore, was it envisioned as a stand-alone application or one that might be incorporated into an existing suite (i.e. MicroStation or

AutoCAD). Discussions confirmed that the prototype was viewed as a conceptual tool and as something that is currently separate from, but complementary to, larger systems such as those mentioned earlier. The designer acknowledged this, but she stressed the importance of a link with existing computer based tools if a new piece of technology where to gain acceptance within the wider design community.

The role of rules within design was considered as interesting by the designer and in particular how such rules can be manipulated in order to create more organic shapes. The designer cited the Scottish Exhibition and Conference Centre (SECC) building, Figure 8.6, as an example of a structure which might well have been conceived of as a single shape which was then transformed into a sequence of shapes that comprise the finished structure. Coincidentally, Designer B cited the same building in the course of their interview.

The issue of rigidity associated with the prototype P2 was raised again when the designer suggested that the resulting shape configurations could be literally overdrawn by a designer and the system then might attempt to abstract alternate rules from such sketches. Furthermore, it was suggested that the system might include the provision of a set of tools to manipulate the shape configurations (e.g. mirror, rotate etc.). These could then be applied to a specific area of the configuration raising the potential of using a different rule configuration on the selected shape. This view raised an interesting issue, not previously considered, that of the system containing two complementary sides. Initially the view was solely that the manipulation of the rules, either by the use of spatial labels or the idea of loose-fit, would drive the production of a shape configuration. What was now apparent was that the configuration had the potential to provide the designer with a blueprint that could then be amended (i.e. by sketching) and could potentially act as the catalyst for the abstraction of new rules. The reflexive quality introduced to the shape-rule relationship raises complex issues at both the theoretical and practical levels. Once again this topic will be dealt with more fully in the future research section of the final chapter.

A discussion concerning the division of space within a new building and in particular the processes that the designer would go through in making such choices were the source of some interesting issues. It was also uppermost in the mind of the designer, as they were involved in just such a project in Glasgow. The designer began by describing the major factors as firstly the design of the core block that runs through the building (e.g. staircases, lifts, toilets etc). This raised an interesting parallel with the idea of 'spines' produced using a loose-fit technique. Up until this point these had been viewed in the context of the placement of buildings. The designer's comment alerted the author to the possibility of buildings having a legibility through such features. For example, the competition to build the headquarters of the Italian Space Agency (ASI) was won by the architect Massimiliano Fuksas, whose building incorporates a sweeping sculptural form that wraps against the front façade (Bell, 2000). Secondly, the client's requirements and thirdly the intended purpose of the building. One of the first tasks to be undertaken was the identification of corridors to enable both primary and secondary circulation. Dimensions of 1500mm for primary corridors and 800mm for secondary were quoted. Escape routes also are identified at this point in the design and where secondary routes must be a maximum of 18 metres from a primary route. The discussion continued about the rules that persist and how these impact on the eventual solutions produced. For example, how columns within a space impact on how that space might be divided (i.e. they have to be a max. of 18 m apart). Also there are rules concerning ceiling heights. The designer commented that all these rules can be broken but they must be done so in a way that the interior will still work. In effect what was being described here was a highly rule based approach to the design of interior office space. Throughout this discussion the designer produced a sketch which is presented in Figure 8.5.

Figure 8.5 Sketch illustrating the layout of a floorplan

The designer was asked to comment on her use of CAD during the process that she had just described. She began by commenting that she used CAD technology throughout the design process and it played an important role during the early conceptual phase. The designer used an example of a call centre to illustrate her use of CAD. In such a task the first thing that she usually did was to 'flood' the office space with rooms and desks. This allowed items to be removed or combined according to what was required. The idea being that it is easier to remove than to add objects to a floor plan. According to the designer this strategy allowed her:

> 'to explore the problem through the production of a large number of alternative solutions.'

These could be produced very rapidly using the CAD system. The exercise helped to clarify and prioritise those attributes of the design which were essential to its overall function and form.

The designer felt that the prototype was appropriate to the conceptual phase of a design but they were also conscious of its overall rigidity in terms of the basic shapes that it utilised within the grammar. She also felt that her ability to view the software with objectivity was hampered by her preconceptions based on her previous use of MicroStation. According to the designer this commercial application provided all the functionality that she required. When asked at what point this software was used during the design cycle the designer responded that it was used early in the activity. In particular in the production of the initial plan drawing of the space. The designer made an interesting comment, which echoed the approach observed from one of the student designers in a previous case study, when they stated that their use of technology at the early stage was 'half and half'. What was meant by this, it was later revealed, was a hybrid approach where computer produced plans were used as a basis for hand sketching - this in turn was re-input into the CAD system. Like the strategy exhibited by the student, a major benefit of such an approach was that the rigour of the system ensured that the scales associated with any ideas were sure to be correct. Indeed some clients preferred 'hand drawn' sketches at the early stage of the design process.

In conclusion the designer felt that the prototype would be useful for the activity of space planning. When a designer is faced with a green field or brown field site of a determined size which has to be divided in ways to accommodate specific requirements of the buildings that it will contain. A scenario was described were a designer might use the prototype to generate configurations of buildings. These in turn could be detailed by another software application. In short, the prototype would act as a basic concept tool which would enable a designer to create a variety of alternative formats for how a space might be divided. This position was similar to the view of another designer who considered that the prototype would be appropriate for the activity of 'master planning'.

8.5.2 Designer B

The interview began with the designer discussing the role of rules within the design process and in particular how he considered that design is governed by rules which are generally implicit (e.g. building regulations, standard part sizes etc). The fact that the system under study made use of simple shape rules and indeed made interaction with them more explicit was viewed as a positive attribute.

An issue that arose during the demonstration of the prototype P1 was that the application of the rules produced very regular combinations of rectilinear shapes. At the time the designer was keen that a degree of uncertainty be introduced to the application of the rules. This desire was articulated in the current version of the software through the introduction of 'loose-fit' rules. The approach produced a favourable reaction from the designer and it was considered that the provision of such a facility would encourage designers to investigate more extreme case scenarios. Two reasons for this proposition were articulated. Firstly, the ease with which the rules themselves could be altered and secondly, the speed with which the resulting shape configurations could be generated. The designer postulated that having to sketch alternatives by hand might encourage a designer to choose safer solutions, thereby alleviating the need to produce multiple sketches. The designer concluded that a system, such as the one demonstrated, might remove such a negative feeling.

The designer began to consider possible approaches whereby designers might usefully interact with rules of the type exhibited in the prototype system. One way which he suggested was the changing relationship of overlap between the shapes that comprise the right hand side of appropriate rules. For example, in the loose-fit rule it was suggested that the designer could set a minimum and maximum percentage of overlap between a rectangle and square. This would enable the system to calculate possible shape combinations based on the degree of overlap. Such a facility it was suggested could be useful for planning the density of housing developments. In particular, density could be used as a criterion through which to generate alternative solutions. Again this topic will be discussed in the context of proposed future research.

As the possible mechanisms for the manipulation of rules were being discussed, the idea of introducing a twofold manipulation was considered. For example, the idea of moving a shape while also turning it relative to another had the potential to introduce such a level of complexity and looseness into a rule that it might result in the production of a variety of more organic forms. In the case of the system this would manifest in a shift and rotate of the rule shapes. The designer cited the example of the SECC in Glasgow as a structure that, in his opinion, is fundamentally rule based in its form Figure 8.6. According to the architects Foster and Partners:

> 'the SECCs form is derived from the internal planning which wraps accommodation, in a series of layers, around the auditorium. The roof encloses the resultant form with a sequence of elegant shells. The roof form is reminiscent of a cluster of ships' hulls, reflecting its position beside the river Clyde on what was once the Queen's Dock.'

Figure 8.6 The Scottish Exhibition and Conference Centre (SECC) in Glasgow (Architects: Foster and Partners)

The designer returned to the problem of urban planning and in particular an activity that he referred to as 'master planning'. This was characterised as being concerned with the design of larger scale developments, as for example the layout for a new village or university campus. The system was considered to be pertinent to this activity as the designer felt that it operated at an appropriate conceptual level that of shape and/or space manipulation. Indeed the rules could be used to generate a variety of alternative layouts, for example with a series of solutions emphasising different house densities. Furthermore the rules might be applied at the level of combinations of dwellings and how they might be located in relation to each other. The concept of spines and the legibility that such rules offered was viewed as appealing to the designer in terms of the overall layout. Also, different combinations can be explored at the level of adjacency between buildings. The designer cited an award winning design for a semi-detached house that created interest through the use of convex angles and colour to emphasis the separate dwellings but also to create a more interesting elevation for the building, Figure 8.7.

Figure 8.7 Semi-detached house Stevenage, UK (Architects: Sergison Bates)

Finally, the designer raised the issue of identifying particular areas of the shape combinations and somehow selecting these as future templates on which a design might be superimposed.

8.5.3 Conclusions

Based on the research reported the following conclusions were made:

- loose-fit rules do successfully introduce a level of irregularity into shape configurations;
- the explicit linkage between rules and design is necessary for design thinking;
- the prototype P2 could be successfully applied to the activity of master planning.

8.6 Discussion

Both designers viewed the introduction of loose-fit rules as a positive step. The resulting 'controlled irregularity' associated with the shape configuration that the rule produced was seen as important to the system's capability to produce unexpected alternatives and hence its potential to inspire creative designs. Despite the inclusion of loose-fit rules, the rigidity of the shape configurations remained an issue. It would appear that this perception of the prototype was linked to the nature of the shapes that comprised the rules, rather than the use of rules in design *per se*. In this case, it was most likely the influence of highly rectilinear shapes used within the rules, which created the perception of rigidity. The rationale behind choosing such shapes was to reduce the computational overhead associated with their transformation during the course of producing a shape configuration.

Both designers acknowledged the use of both explicit and implicit rules within design and also the fact that this does not mediate against the production of innovative solutions. While rules might conjure up images of constraints and restrictions, it is clear that they play a vital role in design. Thus it is one of the more notable successes that all of the prototypes described in this thesis have attempted to make such rules, and their effects, explicit to the designer.

More specifically the prototype system would appear best suited to the activity of space planning or master planning, where alternative solutions can be generated quickly and at a variety of granularities. From buildings within a space, to combinations of dwellings, to the interior space of the dwelling itself, somehow the wilful division of space must take place. It is postulated that the prototype system is well placed to contribute to this activity early in the design process.

The completion of the interviews associated with P2 marked the end point of the research reported in the thesis. The next chapter will reflect on the reported research and will identify a number of areas for future work. The chapter will conclude with a statement of the main findings of the research.

9 Reflections and Conclusions on the Design Process

9.1 Overview

- overview of the research presented in the thesis;
- reflection on the roles of co-operation and shape grammars;
- conclusions based on the research;
- proposals for future work based on the research;
- concluding statement of the research outcomes.

9.2 Review of the Research

The aim of this research was to investigate strategies for the support of design exploration. In particular, how computer based technology could contribute to this activity during the early phase of design. Underpinning this research was the question of whether it might be possible to capture aspects of the dynamic nature of co-operation in the way that we both interact with, and conceive of, technological artefacts. Central to the approach was the ability to generate and communicate alternative solutions. The research explored the position that through the dialogue that accompanies these solutions, it is both possible and desirable for an individual to co-operate with the self through the medium of tools. An initial software prototype P0 was developed to study how alternative solutions could be generated and interwoven into a task based interaction. The task domain of interior design was selected, as its open-ended nature was considered applicable to a co-operative approach. An informal evaluation of the prototype produced favourable feedback concerning the nature of the interaction. In particular, the ability to explore the nature of the generated solution and hence the problem, through the manipulation of rules. However, the feedback was also critical of the overly simplistic design alternatives generated by the prototype due to the poverty of its underlying rule base.

To better understand how a co-operative approach could be applied to the domain of interior design, three case studies of student design projects were undertaken. These studies adopted a tool-mediated perspective and focused on the interdependencies between freehand drawing, physical modelling and CAD. The rationale behind this approach was twofold. Firstly to provide exposure to the practice of design and its associated tools and secondly as a means of informing the design of technological artefacts which seek to complement, rather than replace, this toolset. The studies revealed that both the degree of visualisation offered by each tool and their level of engagement of the designer were critical during the conceptual phase of the design process, in particular during the generation and exploration of alternative solutions. Based on the case studies, a number of scenarios of future systems were generated and presented to members of the professional design community. The resulting feedback provided the basis for an implementation of the prototype P1. The implementation utilised shape grammars as a design based technique for the production and manipulation of alternative solutions. The prototype incorporated the concept of change rules, in the form of spatial labels, which enabled the designer to interactively configure specific rules and thereby create more complex shape configurations. The labels acted as a 'meta-grammar' through which the designer could explore the solution potential of a grammar. The prototype was used as a vehicle to engage in an extended dialogue with design professionals concerning the utility of the approach. An issue that arose was the highly regular nature of the shape configurations generated by the grammar. As a result of these discussions, prototype P1 was extended to incorporate the idea of loose-fit rules. Loose-fit rules introduced an irregularity into the shape configuration. The prototype P2 was presented to two of the three original design practitioners. Their comments (see Chapter 8), together with the insight gained over the course of the research, will inform the direction of future work. This will be outlined later in this chapter. Prior to this it is considered important to reflect on the impact of co-operative behaviour on the research and the applicability of a rule based approach to the support of design thinking.

9.3 Co-operation Redux[1]

It is timely to reconsider co-operative behaviour and the impact that its study has had on the work presented in this thesis. In the mind of the author its influence has ebbed and flowed over the course of the research. At the outset its influence was strong, reaching a peak with the development of the 'co-operative machine', described in Chapter 3. The three key elements of co-operative behaviour among humans, that is shared goals, and agreed language of communication and the ability to generate alternatives and thereby mediate the co-operative process were all specifically represented in the software architecture of the co-operative machine. From this point a subtle shift of emphasis took place, as the study of the design process became increasingly central. Originally conceived as a vehicle with which to articulate concepts thought to underpin co-operation, the domain of design moved to the centre of the research. In hindsight, the critical contribution of co-operation was that it framed the consequent approach to the study of the design process. In particular the role of alternative solutions and latterly the idea of co-operation with the self through the medium of tools. It was for these reasons that the characterisation of design as a co-operative process, rather than a process that exemplified co-operation, is considered to be an important transformation in the lifetime of the research.

9.4 Shape Grammars and Practice of Design

The linkage between language and design has a long tradition. Within this thesis it has been discussed in the context of both drawings (see Chapter 4) and the expression of a design style (see Chapter 6). Indeed, such grammars offer mechanisms whereby computational tools might generate alternative solutions. Shape grammars offered such potential and came from a design tradition. Traditionally such grammars are used to express a given design style, but through the introduction of interaction by means of the configuration of rules that comprise the grammar, a generative capability is possible. In

[1] With apologies to John Updike

prototypes P1 and P2 these change rules took the form of, initially spatial labels and latterly loose-fit rules.

From an academic standpoint the use of shape grammars provided the dual advantages of a generative capability and a legitimacy within the field of design. By using the prototypes as vehicles through which to discuss with design professionals the issues raised by the approach, it was possible to consider the role of shape grammars and in particular how appropriate they were in supporting the actual practice of design. During an interview one of the practitioners commented that maybe designers are always using rules in some way. At a general level this might manifest as a propensity to a particular design style or, at the extreme, as something that they would never do. The implication of this comment was that rules were constantly being applied within design, either implicitly or explicitly in the guise of constraints, requirements or simply personal taste. What grammar based systems offer, in particular those which incorporate 'meta-grammars', is an opportunity to make such rules explicit and to provide an environment where their generative capability can be fully explored through their manipulation. This echoes the sentiments of the 'design worlds' proposed by Schön (1992), specifically the gaining of understanding through exploration and manipulation of both cognitive and physical concepts. At a pragmatic level the characterisation of the design process as one of active construction and the playful exploration of solutions as a means to gain insight and understanding of the problem at hand did appear to match the work practices of the designers who took part in this research.

It is contended that shape grammars provide a viable mechanism for the generation of alternative design solutions and as such will continue to play a central role in the author's development of technologies aimed at supporting the early phase of design. The possible form that such technologies might take will be considered in Section 9.6.

9.5 Conclusions of the Research

The main conclusions of the research are as follows:

- that computer based tools have the potential to support the early phase of design through the production of alternative solutions and the ensuing exploratory dialogue that accompanies this process;
- the introduction of a degree of irregularity into these alternatives offers the possibility to expand design strategies and hence, the potential for creative solutions.

9.6 Proposals for Future Research

During the course of the research a number of themes have emerged which warrant further investigation. This section will outline a series of suggestions for future research. These will be characterised as short, medium or long term undertakings.

9.6.1 Short Term

This section presents work that is directly related to the development of prototypes P1 and P2 and, as such, is considered to be a short term undertaking.

9.6.1.1 Colour Grammars

During the interviews associated with prototype P1, one of the designers commented on the nature of the relationship between shape, colour and space. The designer contended that each could be a potent factor during the envisionment of an interior space, particularly at the early stage of design. As all the prototypes focused exclusively on shape, it would be a natural progression that they incorporate both colour and space. How might such integration work? Space could be incorporated into a grammar with relatively little cost and would require the addition of a Z height for each of the objects. Spatial configurations might be presented as wire-frame models or with the inclusion of surface rendering. Such spatial configurations could then be viewed from a variety of viewpoints. Two of the designers commented that they would like to see the addition of such a facility. Interestingly, the third designer was more reticent about the benefits of such a feature. His concern centred on the power of the visual image and in particular a 3D rendered spatial configuration, as this might overly influence a designer during the delicate early stages of the design process. In short, that the design might be lost within the sophistication of the drawing.

As a consequence it is proposed that colour might successfully be used in conjunction with a traditional shape grammar as an aid to envisionment within the early stages of the design process. Colour grammars have been discussed in the literature (Knight, 1989a, 1994) and operate in a similar way to shape grammars. A colour is assigned to a given shape that, if it overlaps with another, causes the use of a new colour to occur in the overlapped area. Colour grammar rules determine the overlap colour in a similar manner to that of shape grammars. Indeed, it is not difficult to envisage the two grammar types working jointly. The computation of overlap between the shapes is a key factor as the shape configuration is generated. As a preliminary step toward the introduction of a colour grammar, the prototype P1 was altered such that overlap between the shapes of a configuration were identified and shaded as the configuration was being generated. An example of the output produced by the altered P1 is provided in Figure 9.1.

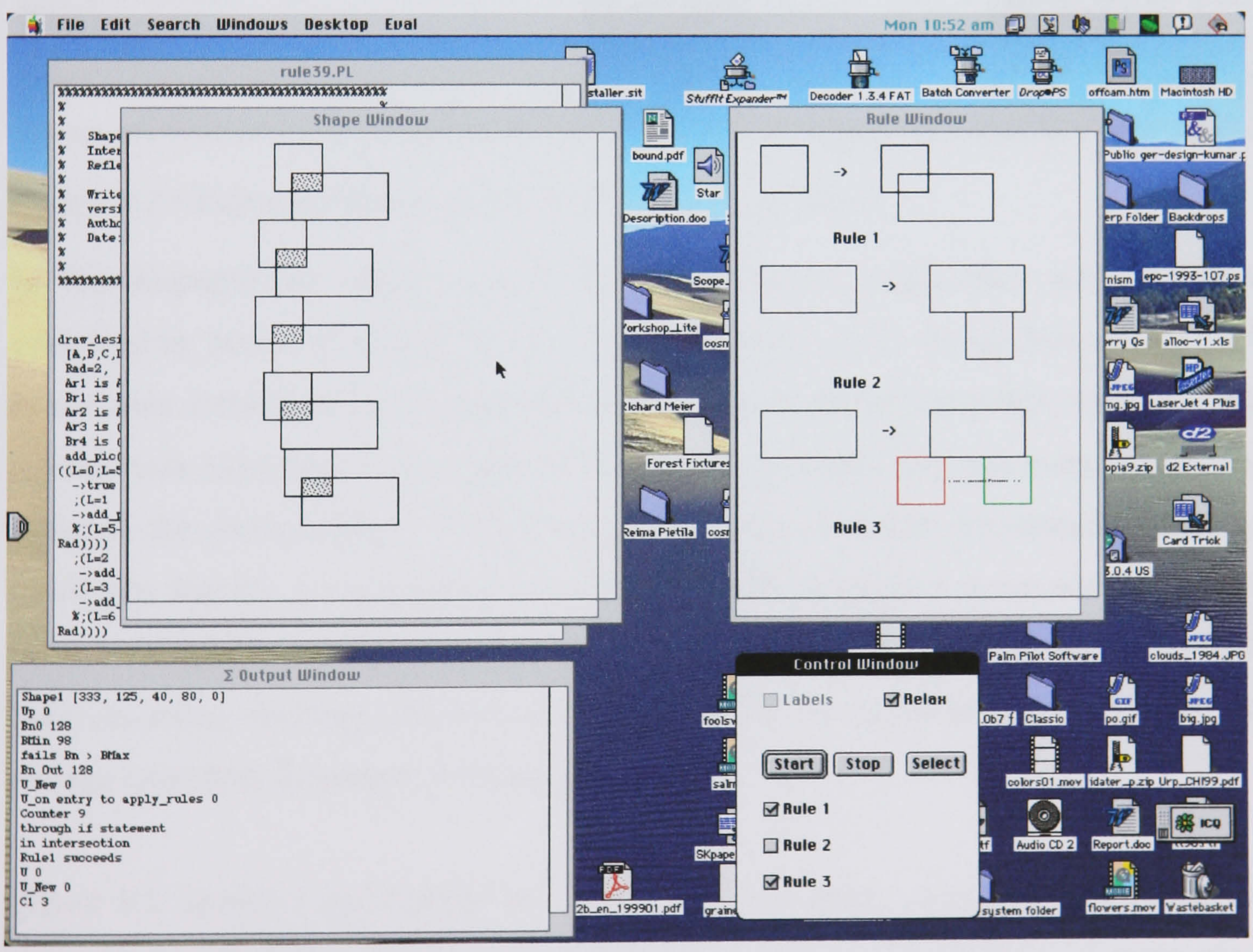


Figure 9.1 Output from altered Prototype P1 in order to illustrate shape overlap. This version also illustrates an early version of the loose-fit rule.

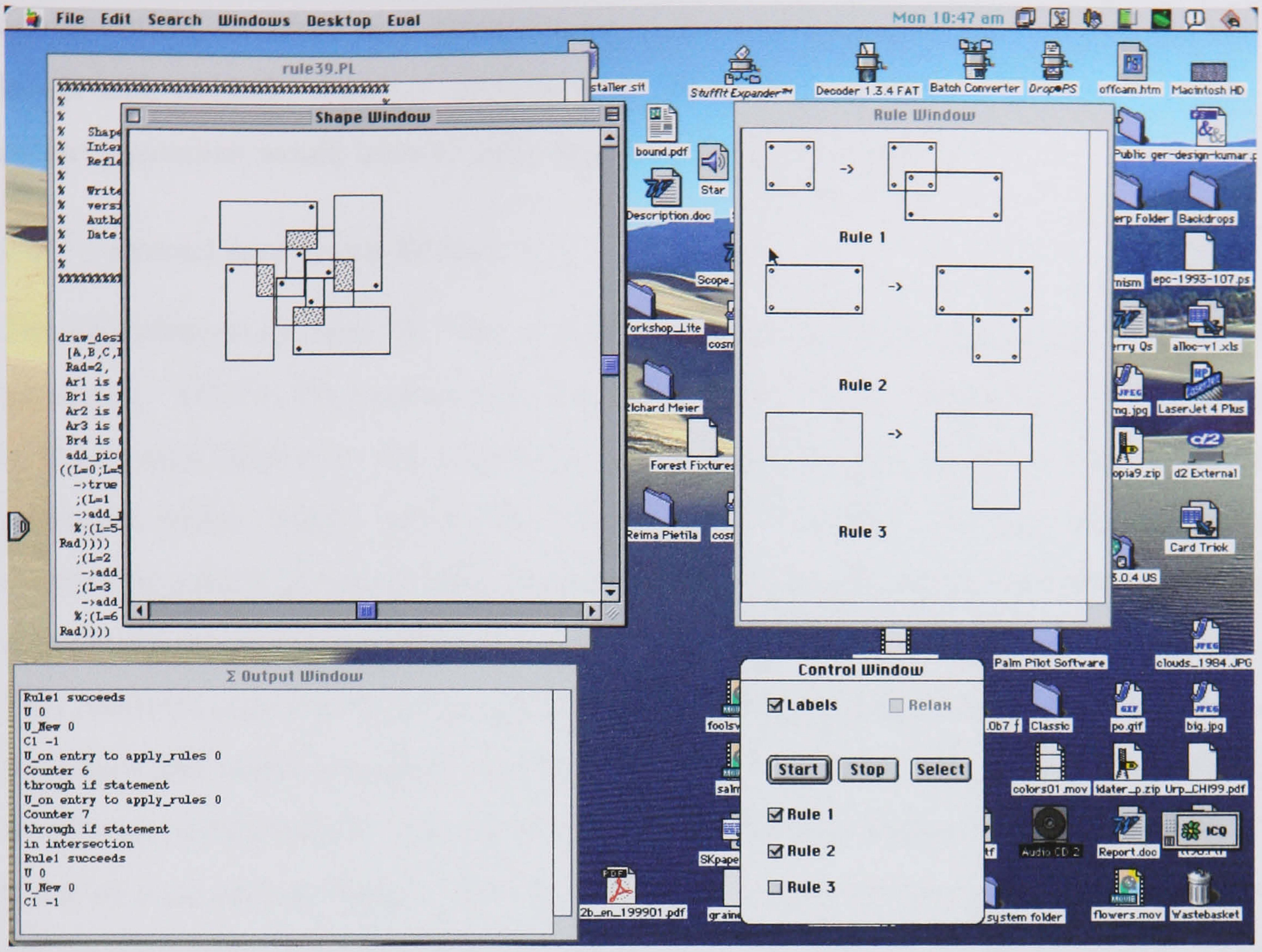


Figure 9.2 Failure to Identify Secondary Overlaps of Shapes.

In this example the shape overlap was calculated in conjunction with a sequence generated by means of a loose-fit rule. No labels were active during this process. When labels were introduced an unexpected problem arose, that of secondary overlap. Shape overlap was calculated with respect to the previous shape that had most recently been added to the configuration. With the transformation of shapes introduced by labels the result was that the positioning of new shapes caused overlap to occur not only with the previous shape, but also potentially with existing shapes that make up the configuration. Such secondary overlaps could not be calculated without significant changes to the shape storage structures developed in prototype P1.

Figure 9.2 provides an example of output were secondary overlaps have failed to be successfully identified. In this case the overlap between the square and rectangle has been successfully identified as these were calculated each time using the penultimate and last shape added to the configuration. The overlap of squares, at the centre of the configuration, occurred as a consequence of the transformation produced by the spatial labels and, as such, were not identified by the overlap algorithm. The introduction of colour grammars would have to solve this computational problem.

9.6.1.2 Extension of Loose-fit Rules

The instantiation of loose-fit rules in Prototype P2 currently operates in terms of shape adjacency. That is, the square on the right hand side of the loose-fit rule could be moved in the X axis relative to the rectangle, thereby enabling the creation of maximum and minimum points within which the square will be located. As part of a discussion concerning master planning with respect to housing developments, one of the designers commented on the desirability of manipulating shape density as well as configuration. This could be achieved by altering the structure of the existing loose-fit rule such that the minimum and maximum shape overlap could be created, thereby setting bounds within which any configuration must adhere. Overlap between shapes could be expressed in terms of a percentage figure. The production of a series of housing schemes each with different densities could be achieved with such a derivative of the loose-fit rule. Loose-fit rules have the potential to let the designer transform, in an infinite number of ways, the relationship between those shapes that comprise the right hand side of rules. The only stipulation being that they provide a minimum and maximum, together with a spine which links them. Figure 9.3 presents a series of increasingly complex examples of how this might be achieved.

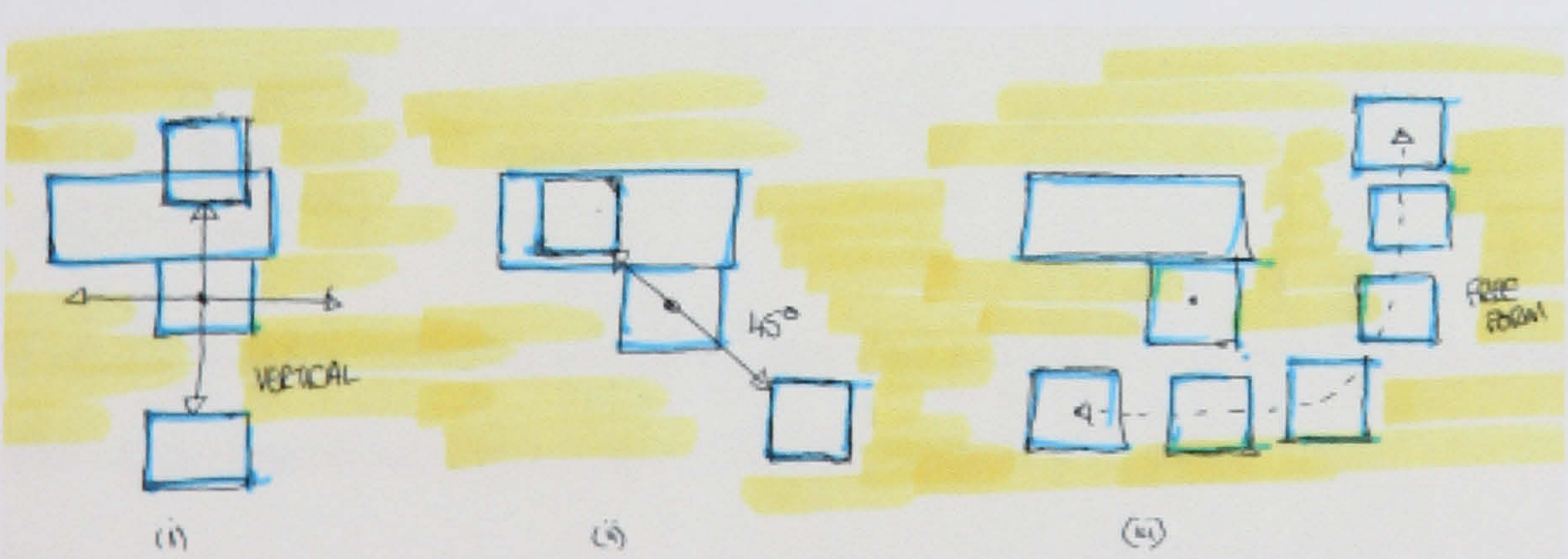


Figure 9.3 Possible Extensions to the Concept of the Loose-fit Rule

9.6.2 *Medium Term*

This section outlines future work classified as medium-term. It is envisaged that this work would require significant changes to be made to the structure of the software developed in prototypes P1 and P2.

9.6.2.1 Manipulation of Shape Configuration

Several of the design practitioners commented that the system did not contain the object manipulation features usually provided by CAD systems. It should be noted that in the main the practitioners used MicroStation and AutoCAD. On further discussion the idea of selecting a part of a shape configuration, or indeed the whole configuration, and applying some transformation upon it was raised. This idea could be extended to allow the production of a configuration to be suspended, an area identified, and possibly a new set of rules applied to the selected area. Tapia (1999) has suggested a similar approach to the manipulation of shape grammars. Figure 9.4 presents this idea diagrammatically.

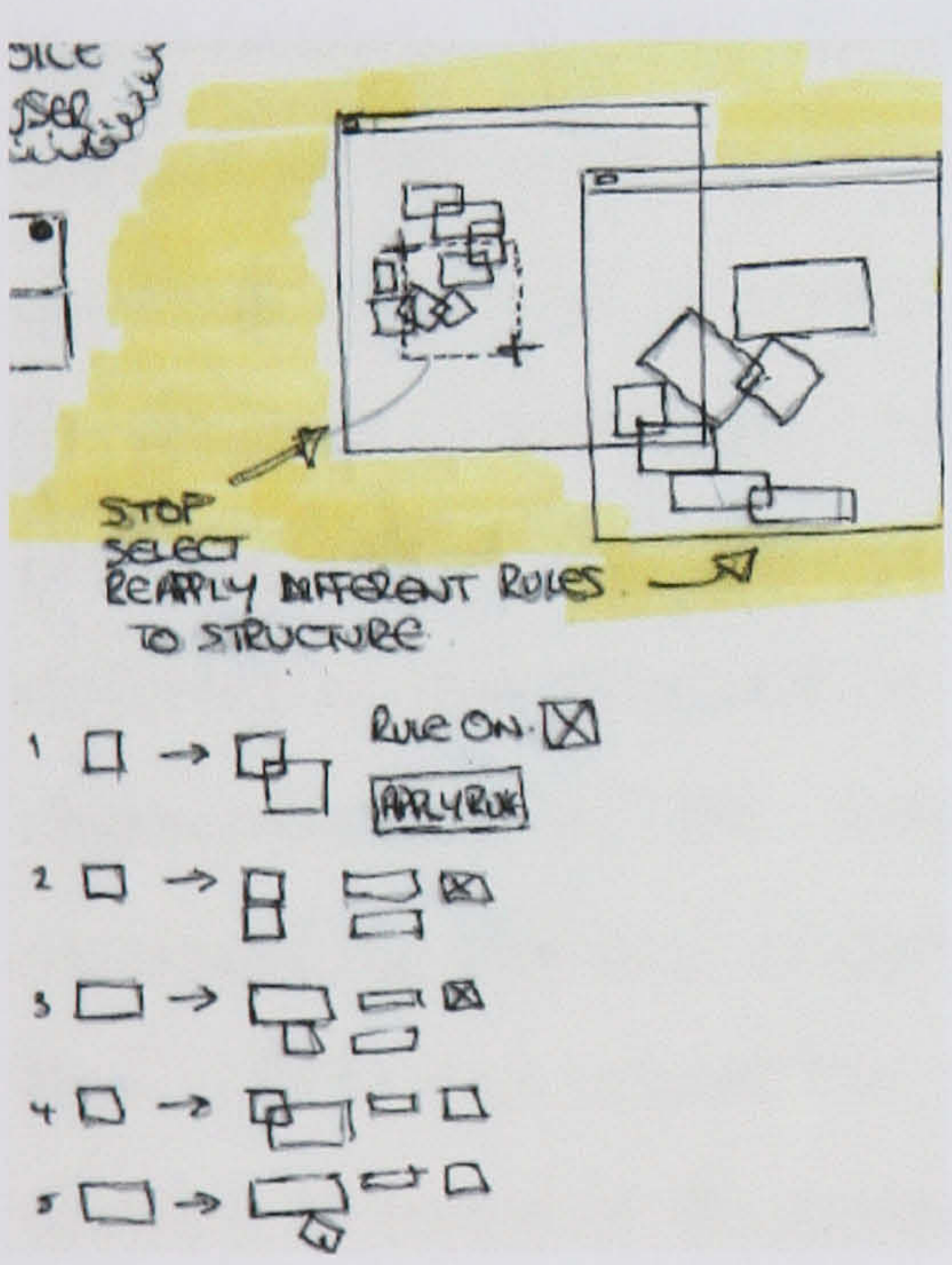


Figure 9.4 Envisionment sketch for the possible suspension of shape configuration and the consequent reapplication of an alternate rule set.

This approach opens up the possibility of shape configurations acting as a generator of new rules which, in turn, could be added to the grammar. Such a reflexive relationship between rule and shape offers the potential of grammars that grow and evolve. Although it is vital that such an approach be viewed with caution in the light of the conclusions concerning the Partner Model in prototype P0. Namely that if the designer creates their own grammar then its potential to spark their imagination could be jeopardised.

9.6.3 Long Term

One major area for long term research that was identified during the research concerned the haptic qualities of design tools. In particular, the role of touch and at a wider level, the role of the body in design. The nature of these attributes and how they might be introduced into the next generation of technologies aimed at supporting design will, it is predicted, become an important research topic, with implications for interaction beyond the domain of design.

9.6.3.1 The Re-Introduction of Touch as a Means of Interacting with Shape Grammars

A theme that emerged primarily during the case studies of tool usage was the role of touch during design. The sense of engagement provided by tools, in particular the haptic qualities associated with physical models, was recognised as being central to design understanding. In particular their ability to enable the consideration of the problem in the context of the whole building, rather than the more limited views provided by hand drawings and CAD. A further quality attributed to physical models was that they enabled the designer to manipulate, through touch, a 3D representation of the building space. The sense of engagement provided by such models was viewed as something qualitatively different to that provided by drawings, whether produced by hand or by CAD. The characterisation of the designer as 'thinking with their hands' while creating or manipulating physical models supports the findings of Candy & Edmonds (1996) and Roy (1993) and echoes the sentiment of Schön (1983) when he described the act of drawing in terms of the designer 'conversing with an image'. The haptic qualities of the physical model provided the necessary degree of intimacy in order to visualise and understand the space. What is being proposed is that the body plays a part in how we make sense of, and interact with, the physical spaces that we design and inhabit and which constitute our environment.

The phenomenologist Merleau-Ponty's (1962) account of 'being-in-the-world' emphasises the importance of the body. This position has been developed, for example by Dreyfus (1996), to explain skill acquisition. Merleau-Ponty places the body at the centre of our relation to the world and argues that it is only through having bodies that we can truly experience space. Not surprisingly a number of ideas underpinning phenomenology has been appropriated by the design community when discussing the acquisition of design skills. This in turn has lead some researchers (e.g. Tweed, 1998) to comment that design based skills are both bodily and cognitive. In the context of how we interact with and through technology such an emphasis on the role of the physical body raises a number of research issues. These can be seen in the work of a number of researchers, most notably Gaver at the Royal College of Art (RCA) and Ishii at MIT who describes his approach as the development of Tangible User Interfaces (TUIs) (Ishii & Ullmer, 1997).

This raises the question of how might technology provide designers with such essential attributes? Indeed, the level of indirection that technology introduces between users and their workaday world has been an important factor in its failure to significantly contribute to the early phase of design (Lawson, 1994). Designers demand tools which provide direct engagement. Current mainstream technologies fail to meet this basic requirement. Possible leverage on this problem might be found in research into Tangible User Interfaces. This work seeks to augment the real physical world by coupling digital information to everyday physical objects and environments (Ishii & Ullmer, 1997). Translating this approach into a design context prompts the following question: why should the act of building a physical model or drawing a plan sketch not also act as a method of inputting that information into a knowledge based system? A similar question was asked by John Frazer during his study of physical design models as input devices, in particular his work on the Universal Interactor and the Walter Segal Model (Frazer, 1995).

Thus a long-term aim for research in this area is the re-introduction of the sense of touch into technology aimed at supporting design. In the context of the research described in this thesis, it is postulated that touch could provide an important mechanism whereby designers in the future might interact with shape grammars. A possible way of achieving such interaction is through the use of back projection techniques, in effect the creation of an interactive drawing board. This opens the possibility of physical objects representing the shapes that comprise a grammar that could, for example, be physically manipulated by the designer as a method of configuring the change rules. The resulting shape configuration could then be displayed on the surface of a drawing board. Figure 9.5 illustrates this idea using envisionment sketches.

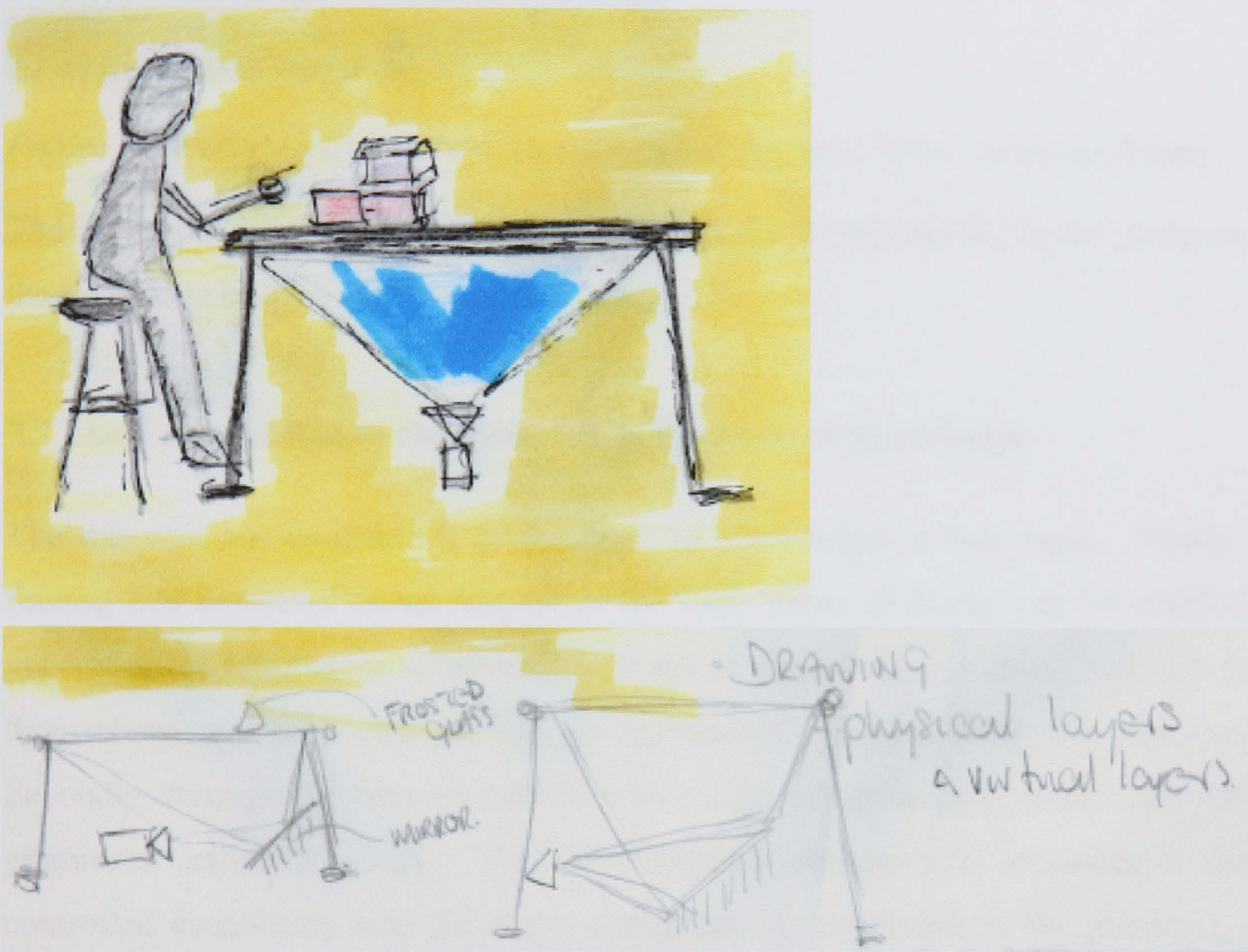


Figure 9.5 Envisionment Sketches for an Active Drawing Board incorporating Shape Grammars

By utilising the metaphor of the drawing board this opens up the possibility of support for collocated design (i.e. a number of designers located in the same physical space working over a shared drawing board, see Figure 9.6). Interestingly, Fischer at the University of Colorado is pursuing a similar line of enquiry with the latest generation of Domain Orientated Design Environments. In the Envisionment and Discovery Collaboration (EDC) (Arias et al, 1998) individuals convene around a computationally enhanced table. This is realised as a touch sensitive surface that allows users to manipulate the computational simulation projected on the surface by interacting with the physical objects placed in the table.

Figure 9.6 Collocated Collaboration over the Envisaged Active Drawing Board.

The development of design tools that return a sense of physicality to the designer will be the next stage of the author's research agenda.

9.7 The Contribution of the Research to the Body of Knowledge

The research has contributed to the body of knowledge in two ways. Firstly, by the finding that computer based support of the early phase of design can be enabled by the generation of alternative solutions. The act of production, coupled with the solutions themselves, act as a catalyst for an exploratory dialogue with the designer's self. Secondly, through the development of a new class of change rule, associated with shape grammars, called loose-fit. This rule allowed designers to introduce a degree of controlled irregularity into the shape configurations generated by the grammar, thereby increasing the likelihood of them inspiring design creativity.

In conclusion, it is my hope that this thesis will serve as a timely reminder both to why computer aided design (sic) poses such a challenge to designers and technologists alike, but also that alternative solutions which can inspire do offer the potential to unlock creativity.

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