THE STRATEGIES USED BY TEN GRADE 7 STUDENTS, WORKING IN SINGLE-SEX DYADS, TO SOLVE A TECHNOLOGICAL PROBLEM

by

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ABSTRACT

The purpose of this study was to investigate the problem-solving strategies of students as they attempted to find a solution to a technological problem. Ten Grade 7 students, who had received no prior technology education instruction, were formed into single-sex dyads and provided with a design brief from which they designed and made a technological solution. The natural talk between the subjects was transcribed. A description of their designing-in-action was added to the transcript. Actions were coded using an empirically derived scheme grounded in both a general problem-solving model and theoretical models of the design process. Segments coded as designing were analyzed using descriptive statistics. This analysis provided the data for mapping, that is, visually representing, the design process used by subjects.

Results showed that novice designers do not design in the way described in textbooks. Their strategy is not linear but highly iterative. Subjects developed their ideas using three-dimensional materials rather than two-dimensional sketches. They were unlikely to generate several possible solutions prior to modelling, but developed solutions serially. The act of modelling stimulated the generation of additional ideas. Evaluation occurred repeatedly throughout their designing.

RÉSUMÉ

Le but de cette étude est d'examiner les stratégies de résolution de problèmes utilisées par les élèves pour élucider un problème technique. Dix élèves de grade sept, sans éducation technologique préalable, ont été groupés en paires de même sexe et assignés une description de problème pour lequel ils devaient trouver une solution technique. Les discussions spontanées des subjets furent transcrites. Une description des étapes de leur cheminement technique y fut ajoutée. Les conduites furent codées selon un schéma empirique basé à la fois sur un modèle de résolution de problèmes de type général et des modèles d'organigrammes d'organisation théoriques. Des segments rattachés au cheminement technique furent analysés en utilsant la statistique descriptive. Cette analyse a servi à faire une représentation visuelle des démarches techniques utilisées par les sujets.

Les résultats semblent indiquer que les novices ne suivent pas le cheminement décrit dans les manuels. Leur stratégie n'est pas linéaire mais très répétitive. Les sujets ont développé leurs idées à l'aide de représentations tri-dimensionnelles plutôt qu'à l'aide de schémas bi-dimensionnels. Contrairement à ce que le modèle théorique suggère, ils n'ont pas développé des solutions possibles avant de commencer le processes technique, mais ils ont développé des solutions par à-coup. L'acte de production de modèles a stimulé la génération de nouvelles idées. Ils ont été évalué tout au long de leur cheminement technique.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

"Theory surely leads to practice. But practice also leads to theory. And teaching, at its best, shapes both research and practice."

(Boyer, 1990, p. 16)

This study derives from the observation of the researcher that untutored Grade 7 students appear to have tacit knowledge of how to problem solve in a technological context. Left to their own devices in an environment rich in three-dimensional materials they frequently design a solution to a problem in unique and creative ways. However, the strategies students use appear to conflict with design process models described in technology education textbooks and curricula. To date, little research has investigated the actual practice of untutored designers to confirm or deny empirically the existence of this apparent conflict. Yet the discovery of a conflict between theoretical models being taught to students and their tacit strategies would have important implications for the teaching and learning of design.

Childrens' experience of designing using materials begins in their earliest years before school. Their play with toys or the objects around them - wooden blocks, empty boxes, textiles - is used imaginatively to simulate the adult world. Witness the ingenuity of childrens' sand castles on the beach, tree houses, skate board ramps, all examples of designing and making in action (Breckon, 1995). Outterside (1993) has observed the emergence of design ability in a three year old child. She concludes that "it is evident that children enter formal schooling with a wealth of knowledge and experience relating to design ... which should be utilized and built upon by the teacher" (p. 49).

It is reasonable to suppose, therefore, that by the time students enter secondary schooling they have a very significant fund of experience with designing, that is, working from problem to solution. The steps they follow to achieve a solution, however, do not appear to conform, either in number or in sequence, to those described in textbooks. Some of the elements of the "correct" process are omitted by students. Others are very evident but are not used in the sequence as described. Hence, the formal teaching of designing appears to conflict with the tacit strategies students bring with them to the technology classroom. According to Outterside (1993) "children ... use the process and process skills [of designing] unknowingly. We should try to raise childrens' awareness of these process skills ... in order to enable them to see and understand, what and how, they are thinking" (p. 49).

Research Questions

The purpose of this study was to investigate the design strategies of students untutored in technology education as they attempted to find a solution to a technological problem. The study was founded on the general question: What design process do Grade 7 students, who have received no prior instruction, use to solve a technological problem? This general question led to the following four research questions which have guided this study:

1. Which steps contained in theoretical models of the design process are present in students' strategies?

This question was investigated by providing subjects with a technological problem to solve. The subjects' actions and task talk (the naturally occurring conversation) while designing were audio and video taped. A protocol containing subjects' task talk while designing, a description of their designing-in-action, and the duration of each discrete action was coded. Coding was informed both by the task talk and responses given during a semi-structured retrospective interview. Descriptive statistics were used to summarize and analyse the percentage of time spent by each dyad on each of the five steps of designing investigated in this study.

2. What design process do Grade 7 students, working in single-sex dyads, use to solve a technological problem?

To investigate this question the design process for each dyad was "mapped" using an XY scattergraph, with codes shown on the vertical axis and the time spent on each code plotted along the horizontal axis.

3. In what sequence do students employ steps of the design process?

This question was investigated by recoding and remapping the data used for Questions 1 and 2. Individual codes were grouped into the five steps found in theoretical models of the design process. This new data set was then mapped using an XY scattergraph.

4. How do the strategies used by students differ from those in theoretical models of the design process?

This question was investigated by visually comparing a map of the subjects' strategy with a map of the theoretical design process.

Technology Education's Place in the Curriculum

Education about using tools to fashion materials to make useful objects is surely as old as humans. Yet only in recent years has technology education, involving both designing and making, become an integral part of general education. As Donnelly (1992) has noted "technology as a component of the secondary curriculum is still in the process of creation" (p. 123). Therefore, unlike established subjects such as mathematics and science, there is little accumulated knowledge about what students should learn and about teachers' understandings of how it may best be taught (Donnelly, 1992; Kelly, Kimbell, Patterson, Saxton, & Stables, 1987; Olson, 1996; Siraj-Blatchford, 1993). However, since technology education is increasingly a mandatory subject for all students from kindergarten to the end of secondary education (Department for Education, 1995; Ministry of Education & Training, 1995; UNESCO, 1983) there is an expanding need for research findings to support curriculum development.

Curricula are dynamic entities constantly evolving in response to changing needs, as envisioned by the society and the educational community in which they operate. There is currently an ever-widening agreement that citizens of the 21st Century will need skills and capabilities significantly different from those taught in the past. These new skills include the ability for creative thinking and problem solving, the motivation to be a life-long learner, and the values and social skills to participate fully in a society whose composition, structure and needs are constantly changing (Department of Education & Science, 1989; Ministry of Education & Training, 1995; Premier's Council, 1990).

Concomitantly, much has been written about how technology education can contribute to and implement these broad aims (Department for Education, 1992; Donnelly, 1992; Ministry of Education & Training, 1995). Accounts tend to focus on the economic benefits to the GNP of a technologically literate populace, the educational value to the individual, and the need for a citizenry which can both make informed decisions about the use of technology and survive in an increasingly technological world (McCormick, 1992; Medway, 1989).

The goals contained in current technology education curricula reflect these broad aims of education. An examination of curricula from the United States

(Illinois, 1983; Indiana, 1985; New Jersey, 1987), Britain (Department for Education, 1995; Schools Council Modular Courses in Technology, 1982), Ontario, (Ministry of Education & Training, 1995) and Quebec (Ministère de l'Éducation, 1983) provides a list of common goals. These include: (a) skills to cope with, live and work in a technological society; (b) understanding the impact of technology on the individual, society and culture; (c) the use of tools and materials; and (d) the ability to design practical solutions to problems.

Current research (Resnick & Klopfer, 1989) urges educators to offer learning experiences beyond what Whitehead (1929) referred to as "inert knowledge". Technology education provides students with opportunities to apply knowledge, to generate and construct meaning. It fosters the kind of cognition that combines declarative knowledge, that is, the *what*, with procedural knowledge, that is, the *how* (Anderson, 1982; Wasserstein, 1995). As Kimbell, Stables, Wheeler, Wosniak and Kelly (1991) point out "there [is] general agreement on certain basic tenets of [technology education]. It is an active study, involving the purposeful pursuit of a task to some form of resolution that results in improvement (for someone) in the made world" (p. 17). And as Breckon (1995) reiterates "technology [education] provides that excellent method of learning - learning through doing" (p. 11).

The "doing" in technology education involves designing and making using a design process. As Barlex (1995) observes "[design] has huge value in preparing young people to understand and communicate sophisticated ideas, and to turn those ideas into real, useful things" (p. 12). Further, the design process is fundamentally a learning process (Outterside, 1993; Rowland, 1993): "By engaging in design the [student] discovers what he or she does not know about a problem and its solution. Filling that gap is a learning process"

(Rowland, 1993, p. 85).

Designing: The Essence of Technological Activity

Technology has been defined in a number of ways (Department for Education, 1995; Down, 1989; McGinn, 1978; Mitcham, 1978). Widely accepted amongst technology educators is a definition which recognizes that the essence of technology lies in the ability to shape the made world in ways which we choose and which will enhance the quality of life (Assessment of Performance Unit, 1981; Department of Education & Science, 1989; Nuffield Design and Technology, 1994a). Technology educators further recognize that at the heart of technological activity lies a problem-solving process using a heuristic referred to as the design process.

Most technology education curricula and textbooks provide a "map" of this process showing a pathway through its apparently discrete stages. But just how accurate are such maps when compared to either what expert designers do in practice or novice designers, that is, untutored students, do when allowed to use their tacit knowledge?

A number of authors have described maps of the design process used by expert designers (Cross, 1994; Jones, 1970a; Lawson, 1990). Lawson (1990) observes, however, that "these maps tend to be both theoretical and prescriptive. They ... have been derived more by thinking about design than by ... observing it" (p. 29). There is little evidence to support the idea that these maps describe what expert designers actually do (Akin, 1978; Darke, 1979; Eastman, 1970; Lawson, 1990).

Similarly, doubt is being cast on the efficacy of design process models contained in much of the technology education literature. There currently exists only a small corpus of empirical findings about children as designers, either at the elementary level (Johnsey, 1995a, 1995b; Outterside, 1993; Roden, 1995), or at the secondary level (Kimbell, Stables, Wheeler, Wosniak, & Kelly, 1991). The studies at the secondary level, however, were conducted in jurisdictions where students receive technology education from Grade 1. Studies of secondary students in those jurisdictions which do not, or did not until very recently, provide technology education at the elementary level have not been carried out. Polya's (1973) remark in the context of mathematics education seems germane: "A better understanding of the ... operations typically useful in solving problems could exert some good influences on teaching" (p. 130).

Theoretical Framework for the Study

A typical form of design process comprises a "characteristic ... sequence of actions" (Hayes, 1989, p. 3): identifying needs and opportunities, understanding and detailing the problem, generating possible solutions, building a solution, and evaluating a solution (Barlex, Read, Fair, & Baker, 1991; Department of Education & Science, 1987; Department for Education, 1992). Akin (1986) has demonstrated how this process shares many properties with a general problem-solving model used in the resolution of ill-structured problems (Reitman, 1965; Simon, 1973), that is, the fuzzy problems that are frequently encountered in real life.

Ill-structured problem solving has been investigated using protocol analysis (Ericsson & Simon, 1984; Hayes, 1989; Hayes & Flower, 1980). A protocol provides "a description of activities, ordered in time, which a subject engages in while performing a task" (Hayes & Flower, 1980, p. 4). Thus viewing designing as a particular form of problem solving allows for the adoption of protocol analysis as a research methodology in this study. It also allows the development of a coding scheme to reflect the problem-solving nature of designing as described in design process models and human problem solving literature (Glaser & Strauss, 1967; Miles & Huberman, 1994; Strauss, 1987; Tesch, 1990). Coded protocols subsequently provide the data for mapping the design process used by untutored designers in this study.

Summary

Technology education as part of general education is a comparatively recent innovation. Until quite recently few examples of practice and even fewer of research data were available to support and guide curriculum development.

Technology educators recognize that the essence of technology is problem solving to meet human needs. The process of problem solving uses a heuristic referred to as the "design process".

The purpose of the present study is to investigate and understand students' pre-instructional design strategies. In the emerging field of technology education such an understanding will add to the empirical basis for the ongoing development of curricula and classroom materials.

The literature related to the theoretical framework for this study, that is, problem types, the nature of design and designing, and models of the design process, will be reviewed in Chapter 2. Chapter 3 will describe the methodology of the study, including the selection of subjects, the procedures for data collection, and the method of data analysis. Chapter 4 will report the data obtained and the results of the analysis. Finally, in Chapter 5, the results of the analysis and some implications for the teaching of technology will be discussed, and recommendations for further research will be presented.

CHAPTER 2: REVIEW OF LITERATURE

"The natural world may or may not have been designed; that, ultimately, is a question of faith. Everything else in the world however, has been designed; that is a statement of fact."

(David Brown, no date)

As technology education has come to prominence during the last three decades, much debate has focussed on the nature of technological activity, the essence of the activity, and how it may best be taught to students. The latest version of the National Curriculum for Design and Technology in England and Wales, for example, states "pupils should be taught to develop their design and technology capability through combining their designing and making skills with knowledge and understanding in order to design and make products" (Department for Education, 1995, p. 2).

Designing (and its attendant making) is now recognized to lie at the heart of technology education. Yet the ways in which students design and how this may best be taught is only now beginning to be understood. How do students, that is, novice designers, go about designing? If, as Cross (1990) claims, "design ability is a form of natural intelligence, of the kind that the psychologist Howard Gardner (1983) has identified" (p. 134), then how can a student's design ability best be developed?

This chapter will review the literature in four areas of current research which contribute to the theoretical framework of the study:

1. Definitions of the term "technology", with particular emphasis on those which have contributed to the current focus of technology education as

designing and making.

2. A description of problem types.

3. The nature of design and designing as a particular form of problem solving.

4. Models of the design process, including a detailed analysis of those which have had the greatest influence on the current form of designing and making in technology education.

The chapter will end with a summary of these four areas of research.

What is Technology?

In order to effectively educate children in and through technology, indeed to understand technology education, it is first necessary to clarify what is meant by the term "technology". Unfortunately, as Hansen and Froelich (1994) point out, while "philosophers, anthropologists, sociologists, historians, and teacher educators continue to study [the term technology] a widely accepted definition remains obscure" (p. 179). Donnelly (1992), for example, identified ten different definitions in the British technology education literature alone.

This difficulty undoubtedly arises from the complex nature and purposes of technology. Even the term itself, derived from the Greek "techne", meaning "art" and "logis" meaning "treatment of" is not universally accepted as the most appropriate to describe what was once known as the "useful arts". Fores and Rey (1986) propose that the German word "technik" is a more accurate term to describe "the functioning of ... man-made [sic] things and the methods used in their manufacture" (p. 37).

Adding to the widespread difficulties of definition are two confusions perpetuated both by the popular media and numerous writers. First, media use of the term in advertising and everyday reporting has many believing that technology is computers, cars, high-fidelity audio equipment, space rockets and the like; that is. the artefacts with which we are surrounded.

The second confusion equates technology with "applied science". There are numerous difficulties with this view, which Sparkes (1993) describes in the following way. First, the goals of science and the goals of technology are quite different. The goal of science is the pursuit of knowledge, often for its own sake. The goal of technology, by contrast, is to create successful artefacts and systems to meet peoples' needs and wants. Secondly, the key processes in science and technology are quite different. In science the two key processes are experimentation and theory creation. In technology design, invention and the production of artefacts and systems are key. Thirdly, science progresses by the process of reductionism, the search for distinct and irreducible concepts. Technology, on the other hand, is holistic, requiring a process of "putting it all together" in order to design successful artefacts. Fourth, science, in its pursuit of objectivity, excludes as far as possible all subjective descriptions of events. Making value judgments is, however, an inherent part of designing artefacts and therefore always a part of technology. Fifth, because of their different goals, science and technology engage in different kinds of research. In science "research" usually means the search for new knowledge and understanding; new data and for causal explanations of them. In technology the search is for the principles underlying better processes, or for better ways of making or doing things. Finally, there is the simple issue of historical sequence. There is ample evidence to show that technology preceded science by many thousands of years. The history of technology provides many examples of technological innovations for which the science was unknown at the time. However, while in the past new technology was based on accumulated experience and knowledge, today it is often based on underlying scientific principles. Today, technology and science are partners. Technology makes much use of science, and science makes much use of technology in achieving their respective goals.

Unfortunately, even some contemporary writers continue to perpetuate this erroneous view of technology as applied science. In the recently published Report of the Royal Commission on Learning: For the Love of Learning (Queen's Printer, 1994) technology was defined as "the application of the problem-solving and reasoning strategies [students] acquire in mathematics, science, and language to concrete problems" (p. 47). Obviously in the view of the Ministry the bow-and-arrow and the steam engine are not examples of technology, for both of these were existent long before the underlying mathematical or scientific principles were understood by their makers. Thus, as Custer (1995) points out "at both the popular and academic levels there is a need for solid conceptual examination of the seemingly familiar term *technology*" (p. 219).

Hansen and Froelich (1994) analyze definitions of technology from a variety of perspectives; an historical viewpoint traces technology's evolution as a discipline; an anthropological view describes technology as a social phenomenon that is an intrinsic part of human culture; a sociological viewpoint examines the effects of technology and the causes of technological change; a philosophical viewpoint is epistemological, asking questions about the knowledge associated with technology; and finally, an educational perspective views technology as a discipline whose essence is the "ability to do".

McGinn (1978) characterizes (rather than defines) technology as a form of human activity that is "fabricative, material product-making or objecttransforming, purposive (with the general purpose of expanding the humanly possible), knowledge based, resource employing, methodical, embedded in a sociocultural-environmental influence field, and informed by its practitioners' mental sets" (p. 190).

Mitcham (1980), in an attempt to elaborate a typology based on functional distinctions, describes a four-dimensional framework for conceptualizing the term. This includes technology as: (a) artefact (tools and manufactured objects), (b) knowledge (scientific, engineering, uniquely technological "how to" knowledge, as well as insight from the social and physical sciences), (c) process (problem-solving, research and development, invention, and innovation), and (d) volition (ethics, technology as social construction, and technology as a social force).

While each of these definitions contributes to an understanding of the nature and scope of technology care must be exercised by those charged with the development of technology education curricula and classroom materials not to focus on any one element to the exclusion of the remainder. For example, past technology education curricula have focussed on the hardware and knowledge components. This is insufficient, for it results in a curriculum that must change as the tools, techniques and materials of technology change. For example, technology defined as artefact only is a restricted definition, for several reasons. First, the hardware does not exist in isolation; it requires what Kline (1986) refers to as "socio-technical systems of use" (p. 2). He provides the example of an airplane, a piece of technological hardware which by itself is no use. It requires the infrastructure of an airport, which in turn requires systems and people to make it function. Hence while it is true to say that an artefact is the product of technology, to define technology in this way neglects both the human dimensions and the impact of technology on humans. This is what Franklin (1990) is referring to when she defines technology as "practice" and talks about the "prescriptive technologies". Finally, defining technology as hardware necessitates a constant redefinition of the term. As the products of technology change so therefore does the definition. This is unsatisfactory.

Technology defined as know-how or knowledge (specifically, knowledge about the use of tools and materials to produce artefacts) is equally inadequate, for it ignores the use to which the technology is put. Yet as Archer (1992) has described, technology is a defining characteristic of humans and their attempts to control the environment. And as Henchey (1987) has pointed out "we miss the significance of the role of technology in our society if we think of technology in terms of tools, machines and techniques" (p. 42).

What is required by technology educators is a definition which reflects the unchanging essence of all technological activity. In other words, what is the commonality of all technologies over time?

An early consensus amongst technology educators defined technology "to be a purposeful activity aimed at meeting needs or satisfying desires through the production of artefacts or systems and drawing on knowledge, skills and personal qualities" (Medway, 1989, p. 4). One of the earliest and most influential operational definitions was proposed by Harrison and Nicholson (1980), who defined technology as "a disciplined process which uses scientific, material and human resources to achieve human purpose: the problem solving activity of design is at the heart of the technological process" (p. 5). This idea that technology has as its focus the satisfaction of human needs and wants through the design and making of products is reiterated in recent curriculum proposals from Scotland: "Technology is a distinct form of creative activity in which human beings interact with their environment to bring about change in response to needs and wants" (Scottish Consultative Council on the Curriculum, 1994, p. 3).

The 1993 recommendations for the UK National Curriculum for Design and Technology (National Curriculum Council, 1993) defined technology as "the creative application of knowledge, skills and understanding to design and make good quality products" (p. 3). In May 1994, in an attempt to clarify the many interpretations by teachers of this statement, the draft proposals for the National Curriculum (subsequently passed into legislation in January, 1995) moved away from a pure definition of the term and toward an operationalized version, which read: "Design and technology capability (emphasis added) requires pupils to combine their designing and making skills with knowledge and understanding, in order to design and make products" (School Curriculum and Assessment Authority, 1994, p. iii). This notion of capability was discussed by Black and Harrison as early as 1985, when they wrote "capability ... calls simultaneously for both action-based qualities and the resources of knowledge, skills and experience ... [it is the] interaction between the *process* of innovative activity [designing] and the *resources* being called upon [which is] the key element of successful ... capability" (p. 5-6).

This concept of capability has been welcomed by teachers, for as Barlex has written for the Nuffield Design and Technology Project (1994b) "[it] avoids the trap of [continually] trying to define ... technology" (p. 1). Additionally, it emphasizes the "distinction between the resources for capability - technical knowledge and understanding, design strategies, and making skills, and the ability to use those resources in designing and making" (p. 1).

The notion of moving away from attempts at a pure definition of technology to one of capability has important implications for this study. If the aim of technology education is to provide opportunities for students to become technologically capable, and if one of the resources for capability is a familiarity with design strategies which the student may use as appropriate, then it might be useful for curriculum developers and teachers to gain an understanding of the tacit knowledge of designing that students bring with them to the technology classroom. For, as Ausubel, Novak, and Hanesian (1978) have written, "the most important single factor influencing learning is what the learner already knows. Ascertain this and teach ... accordingly" (p. 163).

Problem Types

Bringing about change in the made world requires the designing and making of artefacts. This is a form of problem solving, although as Rowland (1993) correctly points out, while "designing involves problem solving, [not] all problem solving is ... designing" (p. 82).

A person is confronted with a problem when he or she wants something and does not know immediately what series of actions can be performed to obtain it (Newell & Simon, 1972). Hayes (1989) writes that "whenever there is a gap between where you are now and where you want to be, and you don't know how to find a way to cross that gap, you have a problem" (p. xii). Reitman (1965) stated that "a system has a problem when it has or has been given a description of something but does not yet have anything that satisfies the description" (p. 126).

Simon (1973) distinguishes between well-structured problems, such as puzzles or arithmetic word problems, and ill-structured problems, the fuzzy problems that are frequently encountered in real life. Well-structured problems mainly require for their resolution the information contained in the problem statement and perhaps other information stored in long-term memory, including procedural knowledge such as knowledge of an algorithm. Ill-structured problems are characterized by the fact that the information required to solve the problem is not entirely provided in the task instructions (Breuleux, undated). Their resolution requires a subject to rely more extensively on resources of long-term memory or to go to external sources for additional information.

Reitman (1965) defined an ill-structured problem as one which required the resolution of a large number of open constraints. Reitman used the term "open constraint" to refer to "one or more parameters the values of which are left unspecified as the problem is given to the problem-solving system" (p. 144).

Technological problems are rarely well-structured. They are more appropriately described as ill-structured. Ill-structured problems lack a clear formulation, require the resolution of a large number of open constraints, have no one "correct" solution, and lack criteria for the evaluation of solutions. In particular, design problems can rarely be fully specified, their goal is usually specified incompletely, and they include many more variables and are therefore innately more complex than well-structured problems.

Various authors (Jones, 1970b; Rowland, 1993; Schön, 1983) argue that the problems with which designers work are so complex, involve so many variables, and are so uncertain that the designer must treat each design as a unique case, not a recurring event.

Reitman (1965), however, moves beyond the notion of a dichotomy of problems and suggests a continuum "which ranges from well-defined formal problems on the one hand to ... ill-defined problems ... on the other" (p. 151). The notion of a continuum is useful if one considers that the category (or point on a continuum) in which a given problem falls obviously depends in part on the problem solver. A problem may be well-structured for the expert problem solver who possesses the requisite knowledge and has practised the relevant problem-solving procedures. Alternatively, it may fall in one of the other categories for one who has insufficient experience or training in solving problems of that type.

This role of the problem solver is discussed by Simon (1973), who argued that many problems first represented as ill-structured problems become well-structured in the hands of the problem solver. According to Simon (1973) "much problem solving effort is directed at structuring problems, and only a fraction of it at solving problems once they are structured" (p. 187). Thus Simon is introducing the idea that initially ill-structured problems become well-structured during the solution process.

According to Rowland (1993) "[in] designing, problem understanding and problem solving may be simultaneous or sequential processes" (p. 84). Robinson (1986) argues that understanding of a design problem is developed through efforts to solve the problem. As both Cross (1994) and Lawson (1990) observed, the problem and the solution are developed in parallel; one does not follow logically from the other, so the process is thus both dynamic and unpredictable.

Thus viewing designing as a dynamic form of problem solving permits the use (for the analysis of data in this study) of procedures, such as protocol analysis, that have been demonstrated to be appropriate in the investigation of problem solving (Ericsson & Simon, 1984).

The Nature of Design and Designing

The term "design" is widely used as both a noun and a verb. As a noun it has two meanings: First, the actual form of an existing object, as in "one of our most popular designs ...", and as an appellation to help sell a trendy or fashionable item, for example, "our designer sunglasses" (Cross, 1990). Second, as a noun it is equally commonly understood to mean a drawing or plan of an artefact. This view of "a design" as a drawing or plan may derive from the fact that most of the theoretical models of the process of design are based on the practice of professionals, who do indeed generate a design which is then passed on (in the form of drawings) to others responsible for its manufacture (Johnsey, 1995b; Jones, 1970b; Lawson, 1990). According to Cross (1990) "the most essential thing that any designer does is to provide, for those who will make the artefact, a description of what that artefact should be like" (p. 128).

As a verb "design" is taken to mean the actual production of a plan for an artefact yet to exist (e.g., "students will design and make ..."). This certainly reflects the reality of the classroom, in which the student is required to act as both the designer and the manufacturer. Johnsey (1995b) uses the term in this broader sense, defining it "to mean both preparing to make a product and the making and testing that often follows" (p. 199).

Many authors have attempted to define both the purposes of design and the nature of the process. A central theme amongst authors writing about the purposes of design and designing is that it is concerned with change; "the activity of designing is ... a goal-directed activity and normally a goal-directed problem-solving activity" (Archer, 1970, p. 286). Simon (1969) thinks of designing as "changing existing situations into preferred ones" (p. 55). Jones (1970b), giving what he regards to be a "universal and ultimate definition of design" (p. 3), says its purpose is "to initiate change in man-made [sic] things" (p. 4). Cross (1979) reinforces the human dimension of the activity by stating that "designing is decision-making at the interface between technology and society" (p. 171). The Design Council's Primary Education Working Group (1987) takes a broader view when they claim that "design is the way in which we try to shape our environment" (Section 3.3, no page). This view is echoed by Archer (1979) who wrote " design ... [may be] defined as the area of human experience, skill and understanding that reflects mans' [sic] concern with the appreciation and adaption of his surroundings in the light of his material and spiritual needs" (p. 20). The Design Council (no date) remind us that "design activity does not operate in a vacuum, and neither can it be taught or studied in one. Every design decision reflects social values and economic priorities" (no page).

There appears to be a widespread agreement amongst design theorists that designing results in the conception and production of new artefacts or systems with practical utility (Archer,1970; Cross, 1982; Rowland, 1993). Yet Rowland (1993) identifies that the process is not one of simply problem solving, but also of problem finding: "Design is a disciplined inquiry engaged in for the purpose of creating some new thing of practical utility. It involves exploring an ill-defined situation, finding - as well as solving - a problem, and specifying ways to effect change" (p. 80). As the Assessment of Performance Unit (1981) concluded "designing is a process of recognizing a need and matching available means with a desired end" (p. 4).

One way of understanding more about designing is to trace or "map" a pathway through the process. The design methodology and technology education literature contains many such maps, and the next section of this chapter examines those contained in a number of technology education textbooks. They are discussed chronologically to show the evolution of thinking.

Models of the Design Process

According to Jones (1970a) "all [models of the design process] are attempts to make public the hitherto private thinking of designers, to externalize the design process" (p. 3). This is nearly always accomplished by a diagram showing the steps in the process and the relationships between them. According to Siraj-Blatchford (1993) "providing a simplified model of the process of design which teachers may adopt heuristically provides for the student what Bruner (1986) has termed scaffolding" (p. 22). Vygotsky (1986) refers to this period when the teacher does for the student what they are not yet able to do for themselves as the "zone of proximal development" (p. xxxv), the gap between what an individual can do alone and unaided, and what can be achieved with the help of more knowledgeable others (Bennett, 1992). For as Schön (1987) has pointed out, one of the difficulties for the novice designer is that:

> Designing is a holistic skill [which] one must grasp ... as a whole in order to grasp it at all. Therefore one cannot learn it in a molecular way, by learning first to carry out smaller units of activity and then to string those units together in a whole design process; for the pieces tend to interact with one another and to derive their meanings ... from the whole process in which they are embedded ... [Nevertheless], it is true ... that design processes may be broken into component parts by strategies of decomposition useful both to practice and to coaching. (p. 158-159)

The literature describing design process models is based primarily on experts' opinions, on their thinking about design, rather than on systematic investigation or experimentally observing it (Lawson, 1990; Rowland, 1993). This literature, on the whole, shares a view of designing as a deterministic, essentially rational and logical process, a set of procedures to be followed. However, it is not clear that designers actually operate as this literature suggests. A few studies of expert designers engaged in the act of designing have been carried out (Akin, 1978; Cross, 1982; Darke, 1979; Eastman, 1970; Schön, 1983) and, as a consequence, empirical descriptions and models of the design process have been developed. Recent studies of novice designers at the elementary level (Johnsey, 1995a; Outterside, 1993; Roden, 1995), at the secondary level (Kimbell, Stables, Wheeler, Wosniak, & Kelly, 1991), and at the university level (Elmer, 1996) are beginning to provide insight into their strategies.

A number of early publications in technology education (Baynes, 1976; Eggleston, 1976; Harahan, 1978) simply described projects suitable for inclusion in a course without describing the process by which a student moved between problem and solution.

Research by the Assessment of Performance Unit (1981) identified activity in technology education as a "summation of skills, knowledge and values" (p. 2). An implicit model of a design process was contained in a description of the skills component:

> The skills ... used in design and technology activity are distinctive and can be grouped into four categories; investigation (recognize existence of a problem), invention (develop and express ideas), implementation (use tools and materials), and evaluation (make judgments about the

efficacy of a solution). (p. 4)

Figure 1 contains a summary of the steps described in twelve design process models to be found in the technology education literature over a period of 24 years. The models are presented chronologically, starting at the left. The earliest, dated 1968, represents one of the first attempts to broaden the technology curriculum from one focussing entirely on the acquisition of craft skills to one which would "develop not only motor skills and craftsmanship, but also many intellectual qualities that hitherto have been associated mainly with other subject areas" (Eggleston, Pemberton, & Taberner, 1968, p. 2).

Each column in Figure 1 describes one model, and uses the original language as far as possible. Identical or nearly identical steps have been aligned horizontally to illustrate the similarities in the models. As will be discussed in Chapter 3 of this study, this alignment permitted the development of a characteristic "sequence of actions" (Hayes, 1989, p. 3) which was later used to develop a coding scheme for data analysis. It should be noted however that not all of the models listed were presented by their authors as linear. As will be described later in this chapter, some were represented in the form of a loop, some as a circle, and some were implicit in the text of the document.

One of the earliest attempts to introduce designing into what had been up to that time skills-based courses was developed at the University of Keele as the Research and Development Project in Handicraft (Eggleston, Pemberton, & Taberner, 1968). While it did not provide a diagrammatic map of the process, a "flexible procedure", containing five steps, was described:

1. A clear statement of the problem.
2. Analysis of the problem using headings such as function, materials,

Step	Eggleston et al (1976) Education through the use of materials	Schools Council (1974) Design for today	Dodd (1978) Design & technology in school curriculum	STEM (1981) Designing for craftwork	Schools Council (1981) Teacher's master manual	Schools Council (1982) Problem solving	Williams (1985) Teaching CDT 8-13	Secondary Exam Council (1986) CDT: GCSE guide for teachers	DES (1987) CDT from 5-16	Barlex et al (1991) Designing starts here	Kimbell et al (1991) Assessment of performance in D&T	DFE (1992) Technology for ages 5-16: NC proposals
Identify situation		Identify problem area Identification of needs from given set of circumstances or observations resulting in design brief					Investigate situation Find a need	Observing a context	The problem Recognise the general problem area	Identifying needs & opportunities	Hazy impressions inside the head	Investigating the design task
Investigate problem			Identification of the problem	Problem Statement of the problem	Identify the problem	Identification & analysis of problem	Identify problem to be solved Write a brief		Specify the exact need			Clarifying the design task
Write design brief	Clear statement of problem							Detailing a problem	Write a brief			Specifying the design task
Specify constraints	Analysis of the problem (function, materials, construction, cost, tools, finish, appearance)	Identification of control factors Imposition of control factors Specification		Restrictions - materials, processes, experience, tools		Limitations & specifications Detailed requirements that have to be satisfied			Write the specification			
Research		Translation of design problem into appropriate terms	Experiment with materials Collection of data Technological considerations	Investigation Questions to be asked about function, shape, size, finish		Information gathering	Collect relevant information	Research	Research Collect data		Discussions, drawings, sketches, diagrams, notes, graphs, numbers	
Generate solutions	Analysis of problem by sketching or other suitable means	Solutions Gathering of specific information related to problem Production of outline solutions	Communication of ideas		Propose solutions Choose the best	Alternative solutions Choice of optimum solution	Investigate possible solutions	Exploring possibilities	Generate ideas & share thoughts with other helpful agencies	Generating a design Thinking up ideas Developing ideas Modelling the best idea	Speculating & exploring inside the head	
Model solution		Selection from possible alternatives Foundation work through "soft" materials	Possible solutions Rejected ideas Selected ideas	Solution Working out Selection		Working drawings	Develop selected solution Produce drawings Make mock-up or prototype		Select & formulate the design proposals	Presenting the best idea	Modelling in solid to to predict or represent reality	Modelling design ideas Developing design ideas
Refine solution	Presentation of the solution (sketches, scaled model)	Production of models Judgements & decisions Consolidation of workable solutions towards realization						Refining ideas Detailing a solution	Model ideas & test		Clarifying & validating inside the head	Communicating design ideas
Plan making			Planning final approach	Planning - dimensions, cutting list, sequence of operations		Planning construction of prototype Start production of prototype		Planning the making	Detail intentions & plan manufacture	Planning		Planning & organising the making
Make prototype	Realization of the design, (perhaps) incorporating minor modifications	Realization Raw materials to end product	Realization	Manufacture	Implement the practical design	Interim evaluation Manufacture a prototype	Make the selected version	Making	Make the solution, refining as necessary	Making	Prototyping Providing solutions outside the head	Using materials, components, tools,equipment & processes to make a product
Test prototype						Testing prototype	Evaluate the finished product		Test the outcome	Evaluating Testing prototype		Testing
Modify prototype						Modification	Modify the finished product					Modifying
Evaluate		Assessment of goal achievement Testing - judgement of the solution in terms of the brief & specification	Evaluation In some open-ended situations the process regenerates		Test & compare with original purpose	Final evaluation Write a detailed report		Evaluation	Evaluate outcome against original need Adjust if possible		Critical appraisal inside the head	Evaluating

Figure 1. Steps in designing and making - a review of the literature

construction, cost, tools, finish and appearance.

3. Analysis of the problem by sketching or other suitable means.
4. Presentation of the solution to the problem by sketches or scaled model.
5. Realisation of the design, perhaps incorporating minor modifications. (p. 11)

The project later became known as the Schools Council Research and Development Project in Design and Craft Education (1974), and their first publication, Design for Today (1974), included one of the earliest maps of a design process for use with secondary school students (Figure 2).

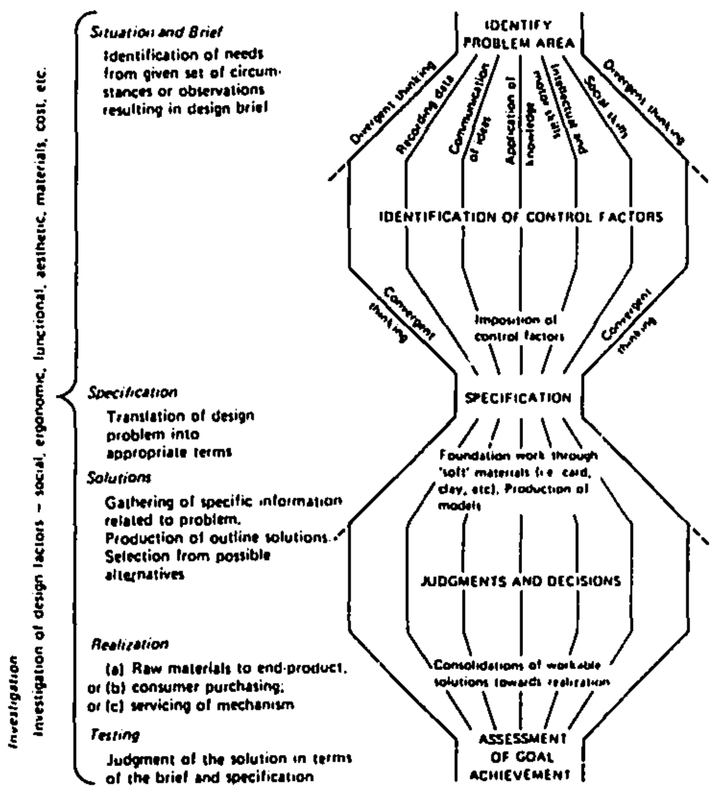


Figure 2. An early model of a design process for secondary schools (Schools Council Design and Craft Education Project, 1974, p. 2)

Numerous maps depicting a linear design process in simple algorithmic problem-solving terms were subsequently published (Dodd, 1978; Engineering Council, 1985; Schools Council, 1982; Scottish Technical Education Modules, 1981; Shaw & Reeve, 1978; Williams & Jinks, 1985). Shaw and Reeve (1978) described a "developmental sequence of four related areas of activity" (p. 7) (Figure 3).

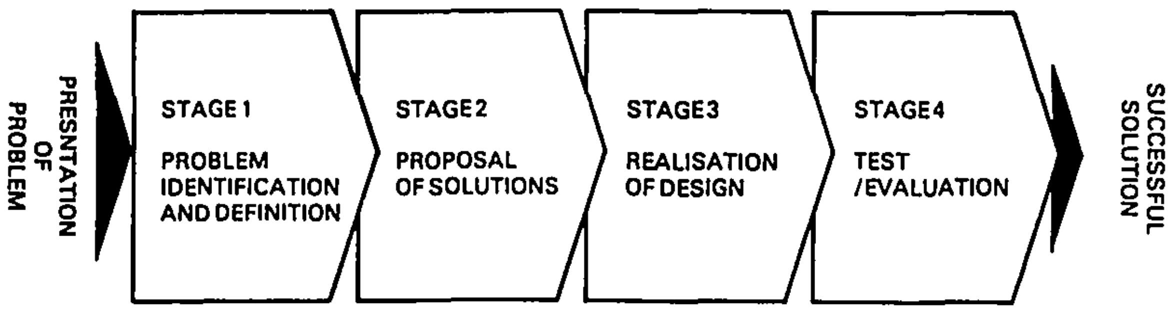


Figure 3. A typical linear design process (Shaw & Reeve, 1978, p. 7)

Williams and Jinks (1985) describe designing as "a journey" (p. 37) and use a "design line" (p. 37) to separate the journey into a number of stages: problem need, first ideas, chosen idea, making, and testing and evaluation. They note, however, that "at the end of our journey ... it may be necessary to 'back track' to make modifications and, occasionally, we have to start all over again from the original problem" (p. 38). Burton (1986) advocated a linear approach since it "is logical and systematic ... and can be broken down into a developmental sequence consisting of a number of related areas of activity" (p. 241).

These linear models went through a considerable amount of development. Many authors recognized the iterative nature of the activity and so added any number of feedback loops to the basic outline. Barlex, Read, Fair, and Baker

(1991) describe the steps in a "design strip" (p. 3), but note that it "is not a straight jacket to be slavishly and linearly followed" (p. 3). Sellwood (1991) presents a design process consisting of a complex figure-of-eight shape, comprising two distinctive stages: (a) the thinking-sharing and interactive stages, and (b) the making and doing stages. However, the accompanying text describes a clear linear route through the model.

Kelly, Kimbell, Patterson, Saxton, and Stables (1987) identify two problems with describing a design process as a set of stages to be followed in a linear way. The first lies in attempts to identify "appropriate activities for each stage" (p. 16). As the authors point out, the activities of sketching or modelling or recording results may each be appropriate during a number of stages. A second difficulty lies in the interdependency of the activities. As Kelly et al. (1987) point out "[when] a pupil chooses to use 'modelling' as an aid to generation and development ... ideas that emerge must be evaluated instantly for the idea to develop [and] the developing idea may require a new line of investigation to see how useful it might be" (p. 16). Lawson (1990) identifies a further problem, when he demonstrates that there is no natural end to a design process. Frequently it is time or cost which terminate design activity.

The next generation of design process models described the activity as an open-ended loop (Department of Education and Science, 1987; Midland Examining Group, 1988). While these models remain linear (Figure 4) there was an increasing acknowledgement that "designing seldom proceeds by way of a series of clearly recognisable stages to a neat solution" (Department of Education & Science, 1987, p. 9).

These models have been helpful guides to the sorts of activities that need to occur in Design and Technology classrooms. However, they have also imposed limits by prescribing "stages" of the process that need to be "done" by students. As the UK Department of Education and Science noted in 1987:

> Used unsympathetically, the approach can reveal a greater concern for "doing" all the stages of the process than for combining a growing range of capabilities in a way which reflects individual creativity and confident and effective working methods. (p. 11)

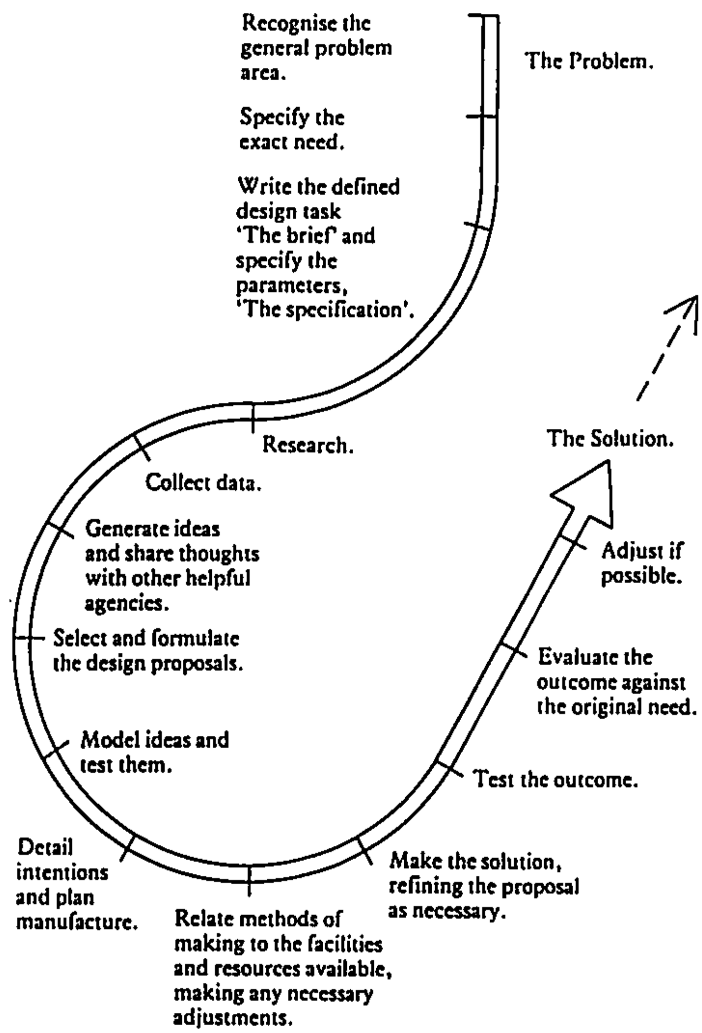


Figure 4. A design loop (Department of Education & Science, 1987, p. 10)

Yet at the same time teachers recognized the need for a model that illustrated "the activities which play a part (emphasis added) in moving from the recognition of an area offering scope for activity to the completion of an end product" (Department of Education and Science, 1987, p. 9). It is also noteworthy that the loop ends with an arrow head pointing to a dashed arrow. This suggests that the process never really ends, but is brought to a conclusion which satisfies a set of requirements at that moment in time (what Simon, 1969, refers to as "satisficing").

The next development further closed the loop and showed that the elements were more interactive (Figure 5).

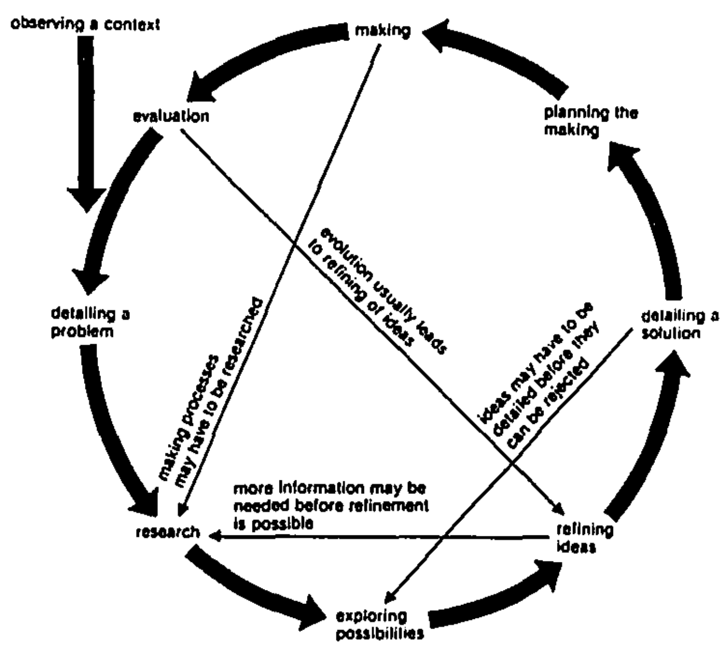


Figure 5. An interactive design loop (Secondary Examinations Council, 1986, p. 10)

In a guide for teachers of General Certificate of Education courses in Craft, Design and Technology (Secondary Examinations Council, 1986) a process, described as "the design loop", is shown in the form of a closed circle with stages of the process distributed around the circumference, to provide "a visual guide to a generalised design procedure" (p. 9). However, as the guide cautions "it does not follow that students have to mechanically work their way around it ... There may well have to be a great deal of jumping about across and around the loop" (p. 9).

This model more closely reflects the ideas of Lawson (1990) who wrote that "the map of the design process must allow for an infinite number of return loops" (p. 27). And Baynes (1992) reminds us that "the processes involved in designing are not linear, ... and they do not always proceed in an orderly way. They are reiterative, spiralling back on themselves, proceeding by incremental change and occasional flashes of insight" (p. 1).

A quite different model of designing has resulted from research by the Assessment of Performance Unit, set up within the UK Department of Education and Science in 1975 to "promote the development of methods of assessing and monitoring the achievement of children at school" (Kelly, Kimbell, Patterson, Saxton, & Stables, 1987, p. i), and later "to analyse the constituent parts of the [design] activity [in order to] make it possible to teach and assess it" (Kimbell, Stables, Wheeler, Wosniak, & Kelly, 1991, p. 19). First described as the "interaction between thought and action" (Kelly et al., 1987, p. 14) and later as the "interaction between mind and hand" (Kimbell et al., 1991, p. 20), the model "reject[s] the idea of describing the [design] activity in terms of the products that result from it, and instead concentrate[s] on the thinking and decision-making processes that result in these products" (Kimbell et al., 1991, p. 20).

The essence of this model (Figure 6) is that ideas conceived in the mind need to be expressed in concrete form before they can be examined to see how useful they are. In other words, "the inter-relationship between modelling ideas in the mind, and modelling ideas in reality is the cornerstone of capability in ... technology" (Kimbell et al., p. 21).

Yet as Johnsey (1995b) suggests "the model is essentially linear and (purposely) vague about what might be happening at any point in the process" (p. 207), reminding us of Lawson's (1990) observation that, in attempting to describe how designers design, "there is not a great deal of action to be seen ... it is what goes on in the designer's mind which really matters" (p. 24).

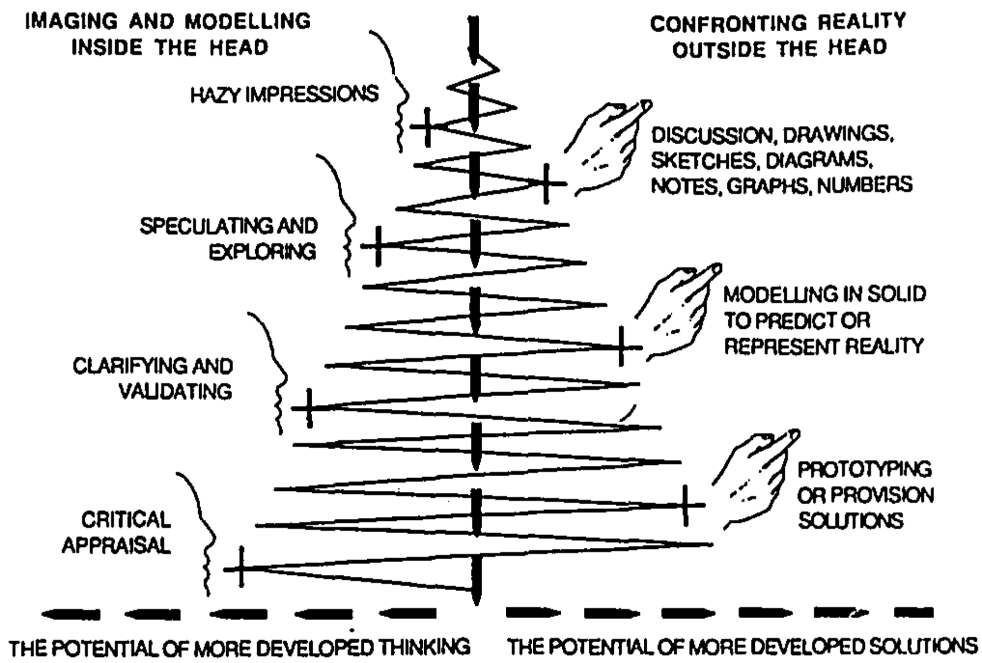


Figure 6. The crucial interaction of mind and hand (Kimbell et al. 1991, p. 20)

Summary

This chapter has reviewed the literature in four areas of research pertinent to this study. First, the essence of technological activity was shown to lie in the process of bringing about change in the made world to meet human needs. This process is referred to as the design process. Discussion emphasized that a central aim for technology education is the development of capability; that is, the ability to design and make an artefact in response to a need. If teaching and learning are to become more effective then teachers and curriculum planners require a more complete understanding of the tacit design strategies that students bring with them to the classroom.

Second, designing was shown to be a particular form of problem solving, involving finding a solution to an ill-structured problem. Viewing designing in this way permits the adoption of a research methodology appropriate to the investigation of problem solving.

Third, use of the term "design" as both a noun and a verb was discussed. This discussion emphasized that in the context of technology education the term embraces both the conception and manufacture of a solution to a problem.

Fourth, a historical survey of design process models contained in technology education literature provided both an insight into their evolution and the theoretical framework for the present study. The survey showed how the early models, which advocated a linear approach to designing, have given way to models which identify a series of process skills which may be used iteratively. The analysis of these models permitted the identification of a set of generic steps which formed the basis of a coding scheme used in the analysis of data.

The next chapter will describe the methodology used for both the collection and analysis of data.

CHAPTER 3: METHODOLOGY

This research investigated the problem solving strategies of students as they attempted to find a solution to a technological problem. The central proposition of this study is that design process models used in Technology Education may conflict with the intuitive strategies students bring to the classroom.

The study is a naturalistic inquiry involving inductive data analysis (Lincoln & Guba, 1985). Naturalistic inquiry requires the researcher to enter the social world of those being studied, observe, and attempt to understand what it is like to be a member of that world (Biddle & Anderson, 1986).

Much naturalistic inquiry involves case studies. A case study is the intensive investigation of a single object of social inquiry (Stake, 1978). The researcher is immersed in the dynamics of a single social entity and able to uncover events often otherwise missed. It is often a process of discovery rather than one of using methods that impose themselves upon the situation (Biddle & Anderson, 1986)

Inductive data analysis in case study research consists of "examining, categorizing, tabulating, or otherwise recombining the evidence to address the initial propositions of [the] study" (Yin, 1989, p. 105). Evidence for case studies may come from a variety of sources (Yin, 1989). The evidence "may be interviews, observations, documents, unobtrusive measures, non-verbal cues, or any other qualitative or quantitative information pools" (Lincoln & Guba, 1985, p. 202).

In this study direct observation of, and retrospective interviews with, multiple cases provided the data for subsequent analysis. Ten subjects were formed into single-sex dyads and provided with a problem statement from which they developed a technological solution. The researcher observed and videotaped the subjects' actions. The natural talk between the subjects was recorded and transcribed verbatim. The researcher subsequently conducted and transcribed a semi-structured interview with each dyad as they watched the videotape of themselves during their problem solving session.

Transcripts of the natural talk were segmented into speech bursts. A description of the subjects' actions was added to the right of each segment. The time at which a change in the subjects' actions occurred was added to the left of each segment, thus allowing calculation of the duration of each period of action.

A coding scheme reflecting the problem-solving nature of designing was developed and used to code actions of the subjects. The natural talk while problem solving and responses made during the semi-structured interview were used to inform the coding. Those actions coded as designing were analysed using descriptive statistics. This analysis subsequently provided the data for mapping of subjects' design strategies.

The Selection of a Research Setting and Subjects

Selection of the Setting

The selection of a school site and subjects was a three-step process: (a) application to a school board for permission to conduct the study, (b) the selection of a school, and (c) the identification of subjects.

Application to conduct the study in a school was made to a large suburban school board in the Toronto region. All external research requests to the Board are first reviewed by the Research Screening Committee. Such requests are made in a standardized format provided by the committee (Appendix A).

Following approval by the committee individual principals are contacted and informed that their school has been suggested for an approved study. Principals agree to participate in the study on an entirely voluntary basis.

Having received permission from the Research Screening Committee to conduct the study, the researcher was requested to meet with the coordinator of Technological Education for the Board, who acted as an intermediary between the researcher and the principal of a senior elementary (Grades 7 and 8) school. The researcher subsequently met with the principal, at which time the purpose and administration of the study were described in greater detail.

At the time of this study the school had a population of 518 senior elementary students (192 Grade 7, 153 Grade 8, and 16 Special Education). It is located in a new suburb containing middle to high-income parents from a variety of ethnic backgrounds.

Selection of Subjects

Ten Grade 7 students (six boys and four girls) participated in the study. They were paired into five single-sex dyads. The decision to have subjects work as dyads reflects the real world of technology, in which most technological development occurs as the result of the efforts of two or more people working cooperatively (Franklin, 1990). Additionally, previous research with dyads (Meyer, 1991) found that while those of mixed gender often do not communicate well or work cooperatively "the use of dyads ... encourage[s] students' conversation as a means to make students' thinking explicit" (Meyer, 1991, p. 14). Further, research has shown that the interaction in a dyad provides much richer data than when subjects work alone (Rahilly, 1991). Tobin (1990) argues that student collaboration "enables understandings to be clarified, elaborated, justified, and evaluated" (p. 407).

Homeroom teachers of the entire Grade 7 student population were provided with copies of a letter describing the research study and a consent form (Appendix B). Homeroom teachers were asked to encourage students to discuss the research with their parents. Those students who returned the completed form comprised the population from which the sample was drawn.

Twenty-one students returned the "letter of consent" signed by both a parent/guardian and the student. Of these twenty-one, ten were identified by the principal and guidance counsellor as meeting the criteria for subjects as specified by the researcher. These criteria were that the students (i) should be articulate, (ii) should be able to work cooperatively, and (iii) have maintained average to above average performance in school work. These criteria are an attempt to ensure a reasonable degree of ability in order that subjects chosen were capable of demonstrating design and technological skills to a level which make detailed analysis possible and worthwhile.

The principal and guidance counsellor paired students, boy with boy and girl with girl, who, in their professional opinion, were compatible and friendly. Those students selected for the study were sent a second letter thanking them for their willingness to participate and indicating the dates and times for both the task and retrospective interview sessions (Appendix C). Those students volunteering to participate but not selected also received a second letter, thanking them for their interest and support (Appendix D). Students selected for the study were assigned a code name (S1 .... S10) and dyads were coded D1 .... D5.

Procedure

The Setting for Data Collection

The researcher was assigned a small, well-lit room adjacent to the school library. Three tables and chairs were provided. Two tables were pushed together to provide a large work surface for the subjects. The third table was used by the researcher for the placement of audio recording equipment. The room was arranged to make the researcher's position and the recording equipment as unobtrusive as possible.

Upon arrival subjects were greeted by the researcher, and fitted with lapel microphones. Once they were seated comfortably the researcher asked the subjects if they were ready to begin. At their signal the researcher began the instructions.

Equipment

Both the problem-solving and the retrospective interview sessions were video and audio recorded. According to Tesch (1990) "audio and video recordings enable the researcher to apply attention to details easily overlooked otherwise, because they are associated with rare events rather than with the usually observed frequently reoccurring events" (p. 47).

The video recordings captured the full record of students' actions as they solved the technological problem: "video provides a multifaceted record, including verbalizations, non-verbal signals, and gross motor movements" (McAlpine, 1987, p. 19). The video camera used a telephoto lens and was placed on a tripod five metres from the subjects. The attached microphone was aimed at the subjects and used to record task talk, that is, the naturally occurring conversation between the two members of a dyad while problem solving.

Audio recordings were also made, using a Sony Walkman Professional (Sony WM-D3) recorder and lapel microphones. These recordings acted as a back-up in case of audio failure in the videotaping, and were used to transcribe the subjects' talk.

The Design Brief

Each dyad was provided with a copy of a design brief that described the technological problem to be solved (Appendix E). The problem, entitled "Paper Tower", read as follows:

> Using ONE sheet of 220 mm x 280 mm white paper and 100 mm of clear tape, construct the tallest possible tower.
> You will also be given pink paper. This you may use in any way as you develop your solution. However, NONE of the pink paper may be used in the tower you submit as a final product.
>
> Limitations:
>
> There is a time limit of one hour.
> The tower must be free standing. It cannot be taped to the floor nor to anything else.
> When you have finished, the tower must stand for 30 seconds before having its height measured.

This particular design brief was selected for five reasons. First, it contains the three elements which Cross (1994) describes as common to all design problems: "(a) a goal, (b) some constraints within which the goal must be achieved, and (c) some criteria by which a successful solution might be recognized" (p. 10). Second, the definition of the design process adopted as one of the bases for this study includes the following steps; understanding the problem, generating possible solutions, modelling a solution, building a solution, and evaluating a solution. Successful completion of the "Paper Tower" task requires each of these steps. Third, informal pilot testing in a variety of educational settings over a number of years by the researcher has demonstrated the task to be one which students enjoy. Fourth, the task does not require any equipment or skills beyond the abilities of Grade 7 students who have received no formal technology education. Finally, the task does not involve the use of dangerous equipment or materials.

Role of the Researcher

The researcher sat in front and to one side of the subjects as they engaged in designing a solution to the problem. The intent was to make the researcher as unobtrusive as possible. The researcher monitored both the video and audio equipment. The video image was framed to ensure that all the actions of the subjects were captured. Audio recording, later transcribed to provide verbal protocols for analysis, was monitored through headphones.

The researcher verified that subjects had understood the instructions, and answered questions throughout the sessions, provided that answers did not assist with a solution to the problem. With the exception of the occasional reminder to speak louder the subjects were not prompted.

Following the recommendation of McAlpine (1987) and Smith and Wedman (1988) the researcher observed and made field notes of dyads' actions during the problem-solving session. McAlpine (1987) used these notes "to make a summary of the [subject's] on-task procedure, that is, what [they] did in order to complete the assignment" (p. 20). Smith and Wedman (1988) stated "we find it helpful to write our observations and insights ... during the ... session" (p. 19).

Instructions to Subjects

According to Hayes, Flower, Schriver, Stratman, and Carey (1985) concise, clear and consistent instructions are essential to ensure that all sessions are as uniform as possible.

The instructions for the problem-solving session were in three parts (Appendix G). Part 1 consisted of a warm-up activity. Ericsson and Simon (1984) demonstrated that when subjects are engaged in tasks involving oral information a warm-up activity is important. Further, the warm-up task should be similar to the main task. In this study subjects were requested to describe some object which they had designed and made at home, how it was made, and the materials used. Following a subject's description the researcher responded with either "That is very interesting. Thank you for sharing it with us" or "That sounds like fun. Again, thank you for sharing it with us". At that point the quality of both the video and audio recordings was checked.

Part 2 of the instructions for the problem-solving sessions described the intent of the research, role of the subjects, and how the session was to proceed. The reason for the audio and video taping was re-emphasized. Subjects were reminded that they should talk normally and naturally during the session.

Before each dyad began designing the researcher checked to ensure that participants fully understood the problem. Each dyad was asked to check that they had all of the materials described on the list. They were reminded that they could use any of the materials but that they didn't necessarily have to use them all. Participants were reminded to work cooperatively and that there was a time limit of one hour.

Part 3 of the instructions, used at the end of a problem-solving session, included a 'thank you' message, a reminder of the date and time for the retrospective interview, and a request to not discuss the design brief with friends until the data collection period was at an end.

The instructions for the retrospective interview (Appendix H) also began with a welcome. As a warm-up subjects were asked to describe, from memory, the problem they solved in the previous session. The researcher then informed the subjects that they were going to watch the video tape of their problem-solving session, during which they would be asked to comment upon some of their actions. In an effort to minimize the response effects (Borg & Gall, 1983) subjects were made comfortable with the idea that if they could not answer a question it was legitimate to say "I don't know" or "I can't remember". The retrospective interview ended with a "thank you" and a reminder not to discuss the interview with friends.

Retrospective Interviews

While the problem-solving session provided an opportunity for the researcher to observe and record subjects designing in action, the goal of the interview was "to probe the subjects' reasoning and intentions which led to their actions" (Meyer, 1991, p. 47). The purpose of using the video during an interview was to "slow down [by starting and stopping the video] the actions so that [subjects could] reflect on the tacit understandings embedded in action" (Argyris, Putman, & Smith, 1985, p. 87).

Within three days of the problem-solving session each dyad returned for a retrospective interview. Subjects were seated in front of a VCR/TV monitor, able to watch clearly the video of their problem-solving session. Each subject wore a lapel microphone linked to a tape recorder. A video camera was positioned so that both the screen and the students could be videotaped, enabling the researcher to document the segment of the problem-solving session referred to by the subjects. The researcher started, stopped, or rewound the tape as subjects were asked to engage in a semi-structured interview. The duration of interviews ranged from 23 minutes, 27 seconds to 54 minutes, 48 seconds.

To prepare for the interview the researcher previewed the video. Specific questions were composed for each interview to clarify particular actions and meanings of subjects' comments. In addition, and following McAlpine (1987), notes taken while the subjects were designing a solution were used for cued recall questioning.

The interview was semi-structured in that the researcher asked each dyad a unique set of questions designed to provide insight into their specific actions. Each interview began with the questions "What sort of pictures entered into your head as you were reading the design brief?" and "What were your first thoughts after reading the design brief?". Interview sessions ended with the researcher thanking the subjects for their participation.

Data Analysis

Transcription

The naturally occurring conversation between the subjects in a dyad, and responses to interview questions were transcribed verbatim from the audio recordings using Microsoft Works V2.0. Each transcript was double-checked for accuracy. Transcripts were typed single-spaced, with a double space between speakers. Speakers were identified by code names (S1 .... S10). Undecipherable speech was indicated by a series of question marks (????).

These transcriptions were then imported into The Ethnograph V4.0, a software package "designed to facilitate the analysis of data collected in qualitative research" (Seidel, Friese & Leonard, 1995, p. 1).

Segmenting

Segmenting, or unitizing, is, according to Holsti (1969) a process whereby "raw data are systematically transformed and aggregated into units which permit precise description of relevant content characteristics" (p. 94). According to Lincoln and Guba (1985) units " are best understood as single pieces of information that stand by themselves, that is, are interpretable in the absence of any additional information" (p. 203).

In this study transcripts were first segmented into "speech bursts" or chunks (Miles & Huberman, 1994, p. 56). A speech burst was defined as "a complete portion of text uttered by a subject without interruption from that subject's partner". Each speech burst was typed on a new line, with the speaker identified by a code name at the left. The start time, in minutes and seconds, of each segment was added to the left margin. Times were read from the digital counter on a Sony VCRPLUS playback machine. Finally, a description of the subjects' actions was added to the right of each segment. Transcripts were then segmented a second time, each new segment delimited by a change in the actions of the subjects. Each segment of action was indicated using a square bracket. Figure 7 shows a sample of a segmented protocol.

S9: 26,04	So it's going something like that?	621 622	Holds up two cylinders into teepee style framework.
S10: 26,07	Yeah. To make some smaller ones too.	624 625	Both continue to roll cylinders
S9: 26,18	Here, I'll roll while you tape.	627	
S10:	OK.	629	Fits 2 cylinders end-to-end
S9: 27,08	Like 20 minutes more.	631	Looks at clock
S10:	Go ahead. ???	633	Rolling & joining cylinders

Figure 7. Sample of a segmented protocol

Coding

Development of a coding scheme. A coding scheme was developed to reflect the problem-solving nature of designing as described in the technology education and human problem solving literature (Department for Education, 1995; Ericsson & Simon, 1984; Kimbell, Stables, Wheeler, Wosniak, & Kelly, 1991). Codes were designed to describe the actions of the subjects, that is, the manifestations of their design thinking. The naturally occurring conversation between subjects as they engaged in problem-solving, and responses made during a semi-structured interview were used to inform this coding of actions.

Ericsson and Simon (1984) postulate "a set of assumptions about the general structure of problem-solving processes" (p. 263). The first of these assumptions, of particular importance for this study, states that "[a] subject's behavior [when problem solving] can be viewed as a search through a problem space, accumulating knowledge ... about the problem as he [sic] goes" (p. 263).

Hayes (1989) describes problem solving as a characteristic sequence of actions: "Finding the problem, representing the problem, planning the solution, carrying out the plan, evaluating the solution, and consolidating gains" (p. 3). The terms used by Hayes to describe this sequence of actions parallel those found in the technology education literature: identifying needs and opportunities, understanding and detailing the problem, generating possible solutions, building a solution, and evaluating a solution (Barlex, Read, Fair & Baker, 1991; Department of Education and Science, 1987; Department for Education, 1992).

According to Miles and Huberman (1994) "a provisional 'start list' of codes [may be created] prior to field work. [This] list comes from the conceptual framework, list of research questions, hypotheses, problem areas, and/or key variables that the researcher brings into the study" (p. 58). This approach is further supported by Tesch (1990) who adds that start codes may also be derived from the literature and tacit knowledge that the researcher brings to the study.

In this study "start codes" were developed by analyzing the design process, that is, problem solving, models described in twelve influential technology education documents spanning the years 1968 - 1992. Common steps in each of the twelve models were aligned horizontally (Figure 1). From this review a generic "sequence of actions" (steps) and a start list of codes were developed (Figure 8).

In Figure 8 the first column lists the steps in a generic model of the design process. The column headed **Code** contains a series of mnemonic codes. The column headed **Definition** contains an operational definition for each code. Miles and Huberman (1994) point out that these definitions are critical, for they

Step	Code	Definition
Identify situation, context, needs	CONT	Exploring a context to identify needs and opportunities
Investigate problem	INPR	Identifying a specific problem to be solved
Clarify problem Write design brief	BRF	Writing a design brief, a clear statement of the problem
Specify constraints & performance criteria	PERF	Specifying constraints and performance criteria
Research	RES	Collecting data relevant to the problem and possible solutions
Generate possible solutions	SOLS	Generating and recording ideas for a possible solution
Model possible solution (drawings, mock-up)	MDL	Modelling ideas using sketches, drawings and mock-ups
Refining & finalizing chosen solution	REF	Refining a possible solution
Plan making	PLMA	Planning the production of a prototype
Making prototype	PROT	Making a prototype
Testing prototype	TESTP	Testing the prototype
Modifying prototype	MODPR	Modifying and improving the prototype in terms of the original need
Evaluating against performance specifications	EVAL	Evaluation of the prototype in terms of the design brief

<u>Figure 8.</u> Codes, derived from the literature, to describe the activity of designing

increase the likelihood of a consistent application of the codes by a single researcher over time and also ensure that other researchers, for example those involved in reliability tests, will be thinking about the same phenomena as they code. In this study definitions were developed to reflect the conceptual structure of designing as evidenced in Figure 1.

Two protocols were selected at random and coded using the scheme in Figure 8. Omissions, gaps and lack of refinement soon became evident. For example, the **Generate possible solutions** category is defined as "Generating and recording ideas for a possible solution". It became clear from the data that generating ideas and recording ideas are quite different and distinct activities. Yet the code set did not make this distinction. Additionally, subjects in this study were not required to explore a context to identify needs and opportunities, identify a specific problem to be solved, or write a design brief. Subjects in this study were provided with a design brief. This ensured that all subjects found a solution to the same problem, thus allowing a more valid comparison of the steps taken to solve the problem.

Therefore a second approach to the derivation of a code set was adopted. Glaser and Strauss (1967) and Strauss (1987) advocate an inductive approach to the development of a code set. Grounded theory (Glaser & Strauss, 1967) states that codes should be "grounded", that is, derived from, the data. Strauss (1987) describes the process as "open coding", defined as "the unrestricted coding of the data aimed at providing concepts that seem to fit the data" (p. 28). Tesch (1990) refers to "empirical indicators", that is, actions, events and words which could be used to develop additional codes.

As a result of this open coding, new codes were derived. Thirty two unique codes were required to complete coding of all the data (Appendix I).

Coding scheme. The coding scheme for this study contains six categories: (1) understanding the problem; (2) generating possible solutions; (3) modelling a possible solution; (4) building a solution; (5) evaluation; and (6) miscellaneous. These six categories were subdivided into 32 unique codes

(Appendix I). Some codes required a subscript. For example, when a dyad made three different mock-ups the first was coded as MMU1, the second as MMU2, the third as MMU3. The addition of subscripts led to the use of 57 codes. A description of each code, along with an example from the protocols, is provided below. Each example contains the following information: the subject's identification code, the segment and line number. Where appropriate the concurrent action of the subject is included in parentheses. For example:

S10:	What if we made yeah, little rolls	553	
	and made it in a teepee style?	554	GEN/MANIP
	(Begins to roll paper into cylinder)		

shows that in lines 553/554 subject S10 suggests an entirely new solution (GEN) to the problem. Simultaneously the subject is manipulating materials (MANIP).

UNDERSTANDING THE PROBLEM CODES

Reading the design brief (RBRF)

Definition: An episode during which subjects read the design brief given by the researcher.

Example: (Subjects silently reading the design brief.)

Discussing performance criteria (DPERF)

Definition: An episode during which subjects refer directly to the performance criteria contained in the design brief.

Examples:	S9:	It has to be free standing	152
		at the end anyway.	153
	S1:	Can't tape it to the floor or	435
		anything else.	436

Discussing constraints (DCONS)

Definition:	An episode during which subjects refer directly to the constraints contained in the design brief.		
Examples:	S2:	Can use only one sheet of paper?	175
	S7:	We didn't use the right amount of tape.	1034 1035
	S2:	We've got an hour so ...	208

GENERATE POSSIBLE SOLUTIONS CODES

Generating possible solutions (GEN)

Definition:	An episode during which subjects discuss an entirely new solution to the problem.		
Examples:	S10:	What if we made yeah, little rolls and made it in a teepee style?	553 554
	S7:	Like a hat or something.	135
	S8:	You could cut it and then roll half of it and roll the other half and stick it together to make it tall.	174 175 176 177

Sketching/drawing a possible solution (DRAW)

Definition:	An episode during which subjects make drawings or sketches of a possible solution.		
Example:	S5:	If we could, let's work on the drawing first. (S5 begins to sketch on pink paper.)	155 156

MODELLING A POSSIBLE SOLUTION CODES

Planning the making of a mock-up (PMU)

Definition: An episode during which subjects discuss ways in which to make a part of a mock-up.

Examples:

S6: We can make little notches at the 228
bottom and they can sort of stand. 229

S10: But then at the end we can get 308
like one piece of tape like if we 309
stack them like that we get one 310
more piece of tape and put them 311
all together. 312
(Subjects discussing ways in which to make sides of tower rigid.)

Manipulating materials (MANIP)

Definition: An episode during which subjects manipulate materials in order to explore one element of a possible solution.

Examples:

S9: Can it be higher than this paper? 196
(Stands piece of paper vertically on table.)

S10: Yeah, just like make some rolls 558
bigger than others. Let's try 559
that. 560
(Begins to roll paper into a cylinder.)

Making a mock-up (MMU)

Definition: An episode during which subjects make part of a mock-up.

Examples:

S1: Start at one corner. 566
(S2 begins to roll a second cylinder.)

S7: Tape the side so it will stay. 186
(Tears off Scotch tape and begins to tape cylinder.)

Refining a mock-up (RMU)

Definition: An episode during which subjects suggest or make a change to a mock-up currently being developed.

Examples:

S1: Let's cut the bottom out, make sure 305
it stands. 306
(Cuts slits in the bottom edge of cylinder and bends them out as tabs.)

S8: I just got to make it even on the 201
bottom. 202
(Uses scissors to modify bottom edge of tower.)

Copying a mock-up (CMMU)

Definition: An episode during which subjects replicate a mock-up in order to verify that it meets the performance criteria and constraints described in the design brief.

Example:

S8: We can, yeah, we can do it over 600
again. Okay and use as less tape as 601
we need. Just to see that it can be 602
done again and that there's not just 603
one that can be done. 604
(Picks up new sheet of pink paper and begins to replicate previous mock-up.)

Checking available resources and materials (ARM)

Definition: An episode during which subjects identify or assess the resources available or remaining to complete the task.

Examples:

S2: How much tape is left? 466

S10: We can always use some, let's 218
take out how much tape we can 219
use. 220

Abandon current solution (ABAN)

Definition: An episode during which subjects indicate they intend to stop work on a mock-up and explore an entirely new solution.

Examples:

S10 Let's do something different. 496

S8: Um, how else could we, we can 165
tape it. 166
(Lays aside current solution.)

BUILDING A SOLUTION CODES

Plan making (PPR)

Definition: An episode during which subjects discuss strategies for replicating a mock-up prior to beginning construction of a prototype.

Examples:

S9: Okay,should you just make it a 953
whole piece? Or just how we 954
had it? 955
S10: Um, OK. Okay that thing is a 956
full strip, and that was about 957
this much. 958
(Subjects trying to remember how to cut materials to replicate mock-up.)

Making a prototype (MPR)

Definition: An episode during which subjects make part of a prototype.

Examples:

S4: Start, start cutting strips out of 210
this. 211
(S4 instructs S3 to begin cutting strips of white paper.)

S5: Okay, tape up the bottom there. 310
(S5 instructs S6 to apply tape to a rolled cylinder.)

Identifying a problem with a prototype (IPPR)

Definition: An episode during which subjects identify a problem in the design of the prototype not previously identified during the design of the mock-up.

Example: S4: Oh, I know why. It wants to go up 589
right? 590
(Folds base of tower in attempt to increase rigidity.)

Modifying the prototype (MODPR)

Definition: An episode during which subjects make a design modification to a prototype.

Examples: S7: Try to make it a little bit wider at 1198
the bottom. 1199
(Compares prototype to mock-up and decides to modify prototype.)

S8: Ah, if we made it square it will 1294
stay. 1295
(Modifies shape of base in way not seen in mock-up.)

EVALUATION CODES

Evaluation of a possible solution (EGEN)

Definition: An episode during which subjects discuss and evaluate a proposed new solution to the problem.

Examples: S2: It won't be that great. 278

S5: That's not quite tall enough. 154

Evaluation of a sketch or drawing (EDRAW)

Definition: An episode during which subjects discuss and make a judgement about a sketch or drawing.

Example: S5: That's not a shape. 190
(Comments on a sketch made by S6.)

Testing a mock-up (TMU)

Definition:	An episode during which subjects test one element of or an entire mock-up as designing continues.		
Examples:	S1:	Let's try to stand it first. (Stands bottom half of tower.)	357
	S7:	Okay, will it stand? (Subject attempts to stand tower.)	199

Evaluating a mock-up (EMU)

Definition:	An episode during which subjects evaluate a mock-up in terms of the performance criteria contained in the design brief.		
Example:	S8:	Okay, how tall is this? (Picks up tape and begins to measure height of tower.)	153

Testing prototype (TPR)

Definition:	An episode during which subjects test one element of a prototype as construction continues.		
Example:	S7:	See if it stands now. Hope so. (S7 attempts to stand a cylinder made from white paper.)	1137

Evaluating prototype (EPR)

Definition:	An episode during which subjects evaluate the prototype in terms of the design brief.		
Examples:	S8:	No. It looks pretty bad but it's standing. Okay I'll take the top. Just don't touch it. (Subject measures height of tower.)	1446 1447 1448
	S5:	I don't think that's going to stay very well. (Attempts to stand tower, points to base.)	342 343

Recording results from a mock-up (RRMU)

Definition: An episode during which subjects record in written form the height of a mock-up.

Example: S7: Um, 15 and 1/2 inches I think. 214
Yep. 215
(Writes height on piece of pink paper)

Recording results from a prototype (RRPR)

Definition: An episode during which subjects record in written form the height of a prototype.

Example: S8: Okay, 22 inches. 1459
S8: Equals, equals 56, 55.9 1461
centimetres. Which equals 1462
559 millimetres. 1463
(S8 records on paper height = 559 mm.)

MISCELLANEOUS CODES

False start (FS)

Definition: A statement which comprises an incomplete thought.

Examples: S3: Or something like ... 285
S7: Yeah, and then it's like ... 485
S8: This is ... 1149

Off-task talk (OTT)

Definition: A statement which is not directly related to the task at hand.

Example: S8: Sounds like Mr. Kirby. 348

Boundary marker (BM)

Definition: Verbal utterances forming a break or link between segments.

Examples: Um, Okay, Uh.

Clarification request (CR)

Definition: A request from a subject to the researcher for clarification.

Examples:

S10:	So just for the tower we can just	110
	use this and that? These two?	111
S2:	So we, I can use this to sketch	156
	on, the ideas and things.	157

Researcher response (RCR)

Definition: Information provided by the researcher in response to a clarification request.

Examples:

S2:	So we, I can use this to sketch on	156
	the ideas and things.	157
R:	Yes, exactly.	159
S10:	When doing the construction is it,	236
	are you talking about using only this	237
	much tape at the end, when it's	238
	finished?	239
R:	That is correct.	240

Warm up (WU)

Definition: Statements made by a subject as part of warm-up activities designed to acclimatize subjects to the task environment.

Example:

S10:	Okay for my Mom's birthday I made	23
	her a sugar jar out of clay, but I	24
	didn't like it very much because it	25
	wasn't proportioned very well and the	26
	lid didn't stay on properly.	27

Researcher introduction: (RINTRO)

Definition: Introductory description of the research project and its administration given to the subjects by the researcher.

Example: See Appendix F for the full script.

Researcher comments (RC)

Definition: Any comment or question from the researcher during the problem-solving session.

Examples:

R: Remind you that you are working as a pair.

R: Keep your voices up a little bit if you can.

Stability and reliability. According to Krippendorf (1980) coding schemes must be evaluated for both stability and reproducibility (inter-coder reliability). Stability is made evident when the same coder codes and then recodes a data set at different points in time (Krippendorf, 1980, p. 130). In this study the entire data set was first coded by the researcher over a three-week period. This was repeated after an interval of two weeks, when the stability was calculated as 82%. Randomly selected portions of transcripts were then recoded over a period of two months until the stability exceeded 90%.

Inter-coder reliability was established by providing three faculty members with a randomly selected section of a transcript containing 10% (100 lines) of the entire protocol. When individual codes were used as a measure of agreement the reliability between the researcher and at least two coders was 79.1%. However, when category of code (e.g., modelling a possible solution) was used as a measure, agreement reached 90.4%. This discrepancy reflects both the short amount of time available to train coders and the researcher's greater familiarity with the coding scheme.

Mapping the Data

Chapter 2 described a number of design process models found in the technology education literature and noted that each is depicted as a graphic model, often linear and frequently containing a number of feedback loops. In this study the design strategy of each dyad is represented in the form of a computer generated "map". Such maps make it possible to search for patterns in a single data set and for regularities in multiple data sets.

As described earlier the transcript of each dyad's problem-solving session was segmented, the start time of each segment recorded, and subjects' actions noted. The transcripts were resegmented into "periods of action" and coded. The time spent on each period was calculated. From this data four statistics were derived: (a) time on code, in seconds; (b) the percent of the total time spent on each coded period; (c) the total elapsed time, in seconds; and (d) the cumulative percent of total elapsed time (Appendix J).

The data were entered into a spreadsheet program (Microsoft EXCEL, V5.0), in which rows 2 to 25 each represent one of the codes developed to describe steps in the design process. Row 1 contains the cumulative percent of total elapsed time, one data point in each column (Appendix M). Additionally, each code in the coding set was assigned a number (e.g., RBRF=2, DPERF=3, DCONS=4), this number being identical to its row number in the spreadsheet.

Each cell in the spreadsheet was then filled with one of these assigned numbers. In the example shown in Figure 9 the subjects were reading the brief (RBRF) from time zero to 2.5 percent of total time. From time 2.5 percent to time 4.4 percent they were drawing (DRAW). Complete data entry is shown in Appendix M. The data were charted using an XY scattergraph with lines. Horizontal and vertical grid lines were added to assist with the interpretation of results.

	A	B	C	D	E	F	G
1	% data task 1	0	2.5	4.4	5.1	5.6	5.9
2	RBRF	2	2				
3	DPERF						
4	DCONS						
5	GEN			5	5	5	5
6	DRAW		6	6	6		6
7	PMU						
8	MANIP					8	8
9	MMU						

Figure 9. Data entry format

Limitations of the Methodology

While dyads are useful for reasons already described, there are some limitations which would not occur if subjects were working singly. For example, there were times during the problem-solving sessions when, instead of working in a cooperative way, the two subjects in a dyad worked individually. When this occurred the researcher prompted subjects with a comment such as "Don't forget you are working as a team". However, for brief periods the recorded actions and task talk are those of two individuals rather than a dyad. At this time coding was based on the major activity. A second limitation, also arising from the use of dyads, occurred when the retrospective interview was dominated by one subject. In this case the researcher attempted to minimize this limitation by using eye contact, friendly body language (such as hand movements while speaking), smiles, and nods toward the less assertive subject.

A third limitation is that the interview asked subjects to reconstruct what they were thinking during the problem solving session. There may be factors which affect these reconstructions, such as subjects' beliefs that they have to defend their actions rather than explain them, or subjects' inability to explain what they did or why. Further, their ideas may have changed as a result of the process and their retrospections may reflect this (Anderson, 1986; Ericsson & Simon, 1984). However, from a research perspective, a difference between the subjects' retrospections and what appears on the videotape (subject actions) may be useful information for the study.

A fourth limitation of the methodology arises from the nature of the assigned task. The model of the design process described earlier in the study has as its first step the situation of a subject in a context and the identification of a need. Clearly, this could not be a part of this research study. Inclusion of this step would remove the commonality of the task and therefore preclude comparison of the process between dyads. As Yin (1989) notes "multiple case study research follows a replication logic" (p. 53).

Summary

This chapter has described the methodology used to investigate the problem-solving strategies of five single-sex dyads as they attempt to find a solution to a technological problem.

Each dyad engaged in a problem-solving session which was both video and audio taped. The audio tapes were transcribed verbatim. These protocols were segmented. The start time for each segment was added, along with a description of the subject's actions.

A coding scheme was developed to include both start codes (derived from the literature) and empirical codes (derived from the data). These codes enabled codification of subjects' actions as they engaged in technological problem solving. Coding of actions, and analysis of the data, was informed both by adjacent task talk segments and responses given in a retrospective interview. The results of the analysis are described in the next chapter.

CHAPTER 4: RESULTS

This study, which investigated the actions of five single-sex dyads as they developed a solution to a technological problem, was guided by four research questions:

1. Which steps contained in theoretical models of the design process are present in student strategies?
2. What design process do Grade 7 students, working in single-sex dyads, use to solve a technological problem?
3. In what sequence do students employ steps of the design process?
4. How do the strategies used by students differ from those in theoretical models of the design process?

In this study the subjects' actions and task talk (the naturally occurring conversation) while designing and making a solution to a technological problem were audio and video taped. The audio tapes were transcribed. A description of subjects' designing-in-action was added to the protocols. Each time there occurred a change in the subjects' actions the time was noted, allowing calculation of the duration of each period of action. Actions were then coded using a scheme based on both theoretical and empirical codes (Appendix I). The task talk and retrospective interviews were used to inform the coding of actions. The actions coded as designing were analysed using descriptive statistics.

This chapter begins with an analysis of the number and distribution of codes for each dyad. The remainder of the chapter presents an analysis of the data organized around the research questions addressed by this study. Analyses of the time (in seconds) and the percentage of total time spent on each code address the first research question, namely: Which steps contained in theoretical models of the design process described in Chapter 2 are present in students' strategies? Question 2 is addressed by mapping the data, which provide a visual representation of the design process Grade 7 students, working in single-sex dyads, use to solve a technological problem. The remaining research questions, "In what sequence do students employ steps of the design process?" and "How do the strategies used by students differ from those in the theoretical models of the design process?" are addressed by further analysis of the maps described earlier. The chapter ends with a summary of the results. The significance and implications of the results for technology education will be addressed in Chapter 5.

Results of Segmenting and Coding the Transcribed Data

The task talk of the subjects was transcribed, segmented, annotated and coded as described in Chapter 3. As a result 547 instances of 32 codes were identified. The frequency of each code by dyad is shown in Appendix K. Row 36 shows that the total number of codes ranged from a low of 71 for Dyad 3 to a high of 164 for Dyad 4.

Since this study focussed on the design process employed by subjects, those codes which describe designing were extracted from the total code set, which also includes miscellaneous codes. As a result 418 instances of 24 codes were identified (Table 1). This frequency of codes for each dyad provided the data for further analysis of the design process used by subjects in this study.

Table 1

Frequency of codes used to describe designing

	A	B	C	D	E	F	G	H
1	Step	Code	Dyad 1	Dyad 2	Dyad 3	Dyad 4	Dyad 5	Total
2	Understand	RBRF	2	2	2	3	2	11
3	Understand	DPERF	2	0	0	1	1	4
4	Understand	DCONS	3	3	0	0	1	7
5	Generate	GEN	6	7	5	7	10	35
6	Generate	DRAW	3	2	2	0	3	10
7	Model	PMU	0	0	1	10	2	13
8	Model	MANIP	4	5	3	1	4	17
9	Model	MMU	7	0	2	16	13	38
10	Model	RMU	14	0	1	21	13	49
11	Model	CMMU	0	0	0	1	0	1
12	Model	ARM	6	3	4	9	6	28
13	Model	ABAN	0	1	0	1	2	4
14	Build	PPR	0	3	0	1	2	6
15	Build	MPR	3	9	3	6	3	24
16	Build	IPPR	0	3	6	0	0	9
17	Build	MODPR	1	17	7	16	0	41
18	Evaluate	EGEN	0	0	0	0	0	0
19	Evaluate	EDRAW	0	1	0	0	0	1
20	Evaluate	TMU	3	0	1	17	7	28
21	Evaluate	EMU	10	0	2	15	7	34
22	Evaluate	TPR	1	11	0	5	1	18
23	Evaluate	EPR	6	6	6	13	1	32
24	Evaluate	RRMU	0	0	0	4	0	4
25	Evaluate	RRPR	0	2	1	1	0	4
26	Total		71	75	46	148	78	418

Question 1. Which steps contained in theoretical models of the design process are present in students' strategies?

As described in Chapter 2 the technology education literature frequently depicts the design process as a "characteristic sequence of actions" (Hayes, 1989, p. 3) containing six steps: (a) finding the problem, (b) understanding the problem, (c) generating possible solutions, (d) modelling a possible solution, (e) building a solution, and (f) evaluating the solution. Often this sequence is depicted in the form of a flow chart, sometimes in a simple linear form but most recently showing numerous feedback loops and inter-connections between the steps.

An idealized "map" of a subject's sequence of actions, based on the models in the technology education literature, might be expected to appear as shown in Figure 10. The steps in the process are shown on the vertical axis. Time spent on each step in the process is represented by the bold horizontal lines. Having identified a problem to be solved students are expected to begin by sketching (generating) a number of alternative solutions, ultimately selecting the one which seems the most appropriate. Having selected a best solution, students would then be expected to spend considerable time modelling and making a solution, before evaluating the end product.

In Figure 10 the time spent on each step reflects a subjective interpretation based on a distribution implicit in a number of theoretical models (see Figure 1). Step 1 (finding the problem) and Step 2 (understanding the problem) require the least amount of time. Steps 3 and 4 (generating possible solutions and modelling a possible solution) together require the greatest time. Step 5, building a solution, requires approximately the same time as either Step 3 or Step 4. According to theoretical models, evaluation (Step 6) occurs at the conclusion of Steps 3, 4 and 5.

However, as described in Chapter 3, to ensure that they all found a solution to the same problem, thus allowing a valid comparison of their sequence of actions, subjects in this study were not required to find a problem to be solved but were provided with a design brief. An idealized map of a design process subjects might be expected to use in this study is shown in Figure 11.

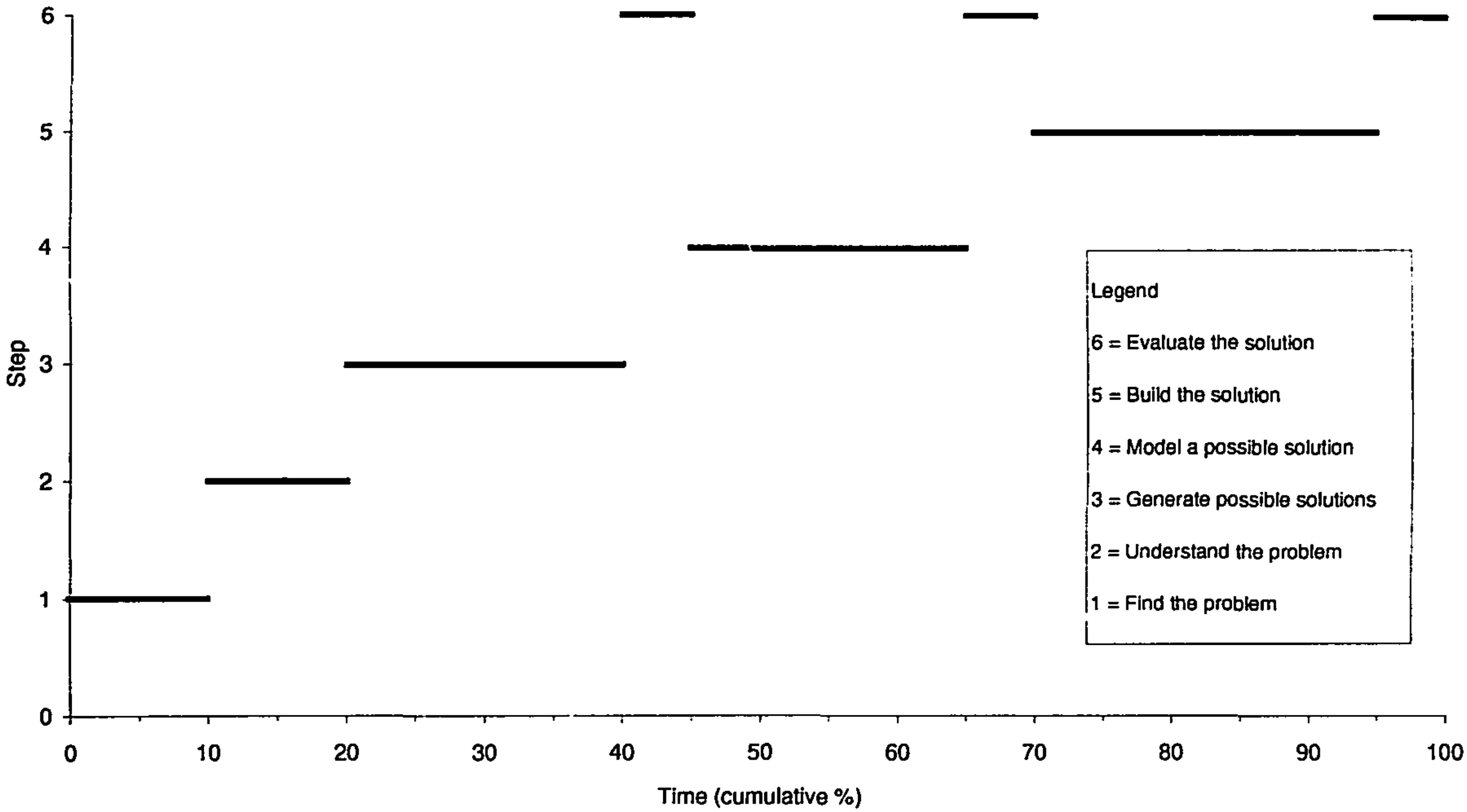


Figure 10. Map of the theoretical design process described in the literature

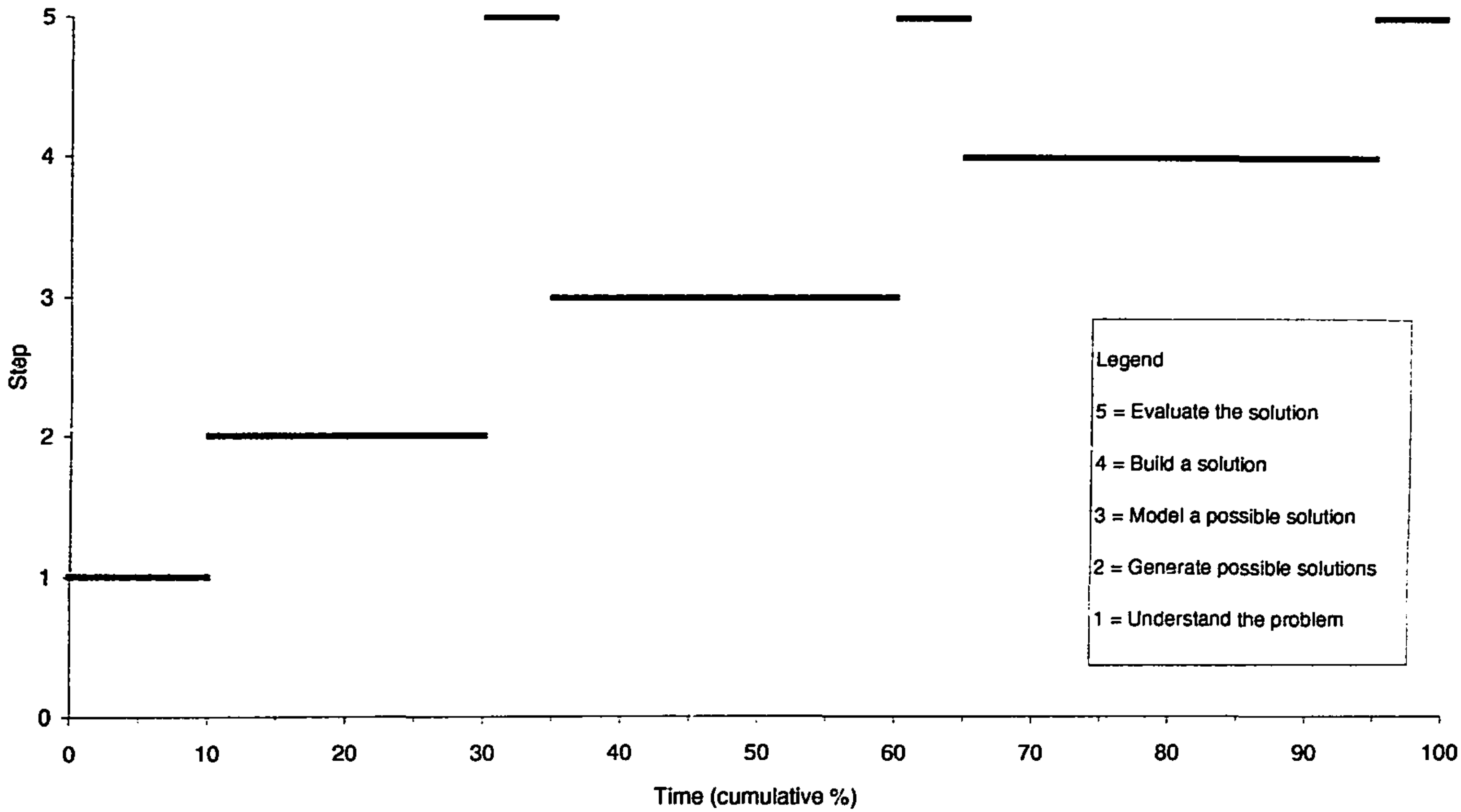


Figure 11. Map of the five-step theoretical design process used in this study

The five steps and related codes are used as the organizer for the next section of this chapter, an analysis of the steps contained in theoretical models of the design process present in students' strategies and the time devoted to each step.

Table 2 summarizes the percentage of time spent by each dyad on each of the five steps of designing investigated in this study. Figure 12 shows the results graphically.

Table 2

Distribution of time spent by dyads on each step of the design process

Time (secs)
% of time

Step	Dyad 1	Dyad 2	Dyad 3	Dyad 4	Dyad 5
Understanding the problem	117 *6.0*	93 *5.0*	48 *6.44*	132 *3.58*	85 *2.88*
Generating possible solution	120 *6.16*	199 *10.69*	112 *15.04*	149 *4.05*	330 *10.87*
Modelling possible solution	1064 *54.57*	130 *6.99*	142 *19.05*	1654 *44.86*	1902 *62.62*
Building solution	219 *11.22*	1077 *57.88*	264 *35.44*	843 *22.87*	342 *11.26*
Evaluating	430 *22.04*	362 *19.45*	179 *24.03*	909 *24.67*	378 *12.44*

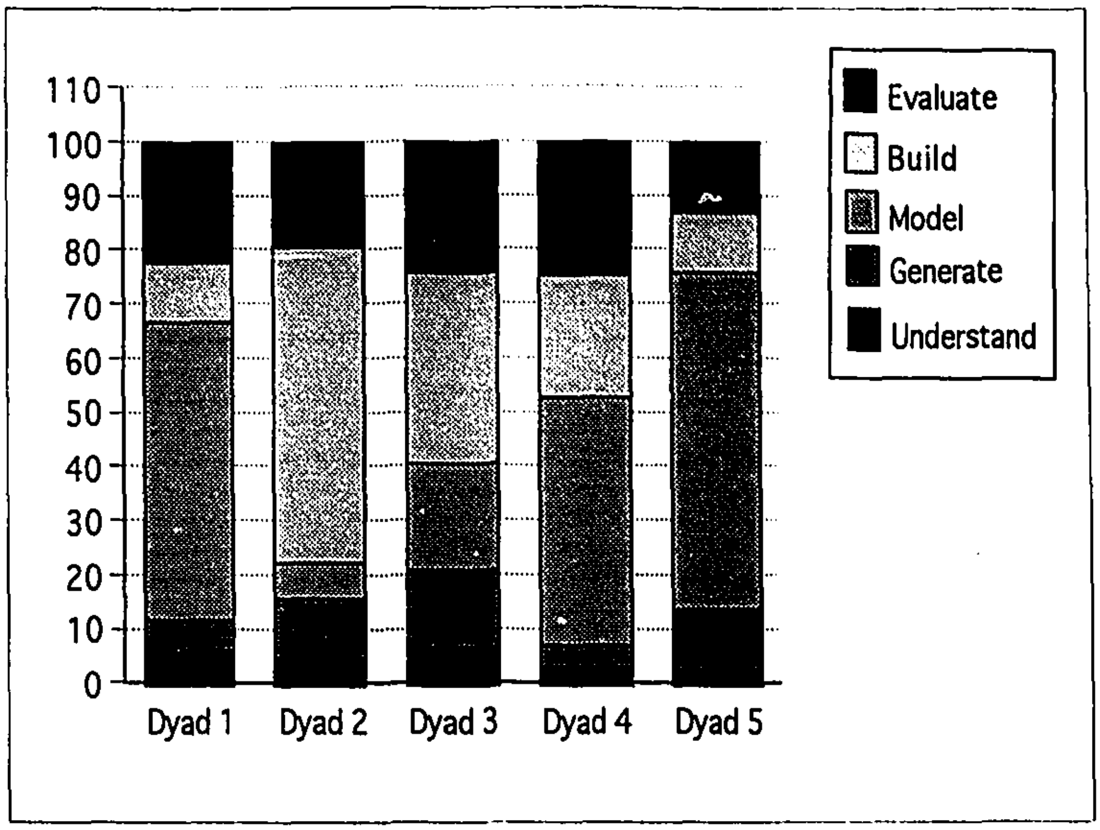


Figure 12. Distribution of time spent on each step in the design process

In order to understand the problem subjects were required to read the design brief at the outset of the task. With the exception of the subjects in Dyad 4, who read parts of the design brief on two further occasions, dyads read the brief on only one further occasion. The time spent reading the brief, discussing or referring to performance criteria and constraints ranged from 2.88% to 6.44 % of the total time on task.

According to theoretical models of the design process subjects should have spent a considerable proportion of their available time generating possible solutions (usually by sketching and drawing) prior to modelling in resistant materials. In this study the time spent "modelling in the mind's eye" and graphically recording possible solutions ranged from 4.05% to 15.04% of the time on task. By contrast, subjects spent a considerable time modelling possible solutions in three-dimensional form. Table 2 shows that the time subjects spent modelling ranged from 6.99% to 62.62%. Dyad 2 is the obvious anomaly, but as will be described later, this dyad moved almost immediately from reading the design brief to building a prototype.

The time spent building a prototype, in essence replicating a successful model making only minor design changes, ranged from 11.22% to 57.88% of dyads' time. Evaluation, whether testing one element of a solution or assessing a solution in terms of the design brief, occupied between 12.44% and 24.67% of dyads' time.

In summary then, subjects divided their time-on-task in approximately the following way: 5% understanding the problem; 9% generating possible solutions; 38% modelling a possible solution; 28% building a solution; and 21% evaluating solutions.

The next section of this chapter provides a more detailed analysis of the data contained in Table 2.

Understanding the problem

In order to understand the problem subjects were required to read the design brief provided by the researcher. Since the brief was in written form subjects could refer back to it whenever they felt it necessary (RBRF). Evidence of attempts to understand the problem were also reflected in explicit references to the performance criteria (DPERF) and constraints (DCONS) imposed by the task.

Table 3 summarizes the total time, in seconds, and the percentage of total time spent by each of the dyads on codes related to understanding the problem.

Table 3

Time spent on the step "Understanding the Problem"

	Time(secs) *% of total time*				
Code	Dyad 1	Dyad 2	Dyad 3	Dyad 4	Dyad 5
RBRF	56 *2.87*	65 *3.49*	48 *6.44*	70 *1.90*	73 *2.40*
DPERF	17 *0.87*	0 *0*	0 *0*	49 *1.33*	10 *0.33*
DCONS	44 *2.26*	28 *1.51*	0 *0*	13 *0.35*	2 *0.07*
Totals	117 *6.0*	93 *5.0*	48 *6.44*	132 *3.58*	85 *2.8*

The total time subjects spent attempting to understand the problem ranged from 2.80% to 6.44% of total time on task. The time subjects spent reading the design brief, both at the beginning of the task and while designing, ranged from 48 seconds to 73 seconds. One subject in Dyad 4 read the design brief aloud: the remainder read silently.

Very little time was spent referring to or discussing either the performance criteria or the constraints. Two dyads made no explicit reference to the performance criteria and one dyad made no explicit reference to the constraints.

Generating Possible Solutions

Subjects could generate one or more possible solutions to the problem in two ways; by thinking about and then discussing with their partner a possible solution (GEN), or by sketching/drawing a possible solution (DRAW). Subjects spent very little time on either of these activities (Table 4).

Generating possible solutions by thinking and discussion occupied between 2.05% and 5.53% of subjects' time. Sketching or drawing possible solutions occupied between 0% and 1.85% of the time (0 to 36 seconds). Interestingly, four of the dyads spent time simultaneously discussing and sketching possible solutions (GEN/DRAW), and all five dyads spent time simultaneously discussing a possible solution while manipulating materials (GEN/MANIP).

Modelling a Possible Solution

According to Evans (1992) a model "translate[s] ideas into a three-dimensional form" (p. 42). In this study subjects were provided with a range of materials which could be used to "translate drawings into a more representative format" (Evans, 1992, p. 43) or explore one or more elements of a solution.

According to the literature, subjects, having generated a possible solution through discussion and drawing, should engage in a series of actions to explore the feasibility and efficacy of their proposed solution prior to making a prototype. Planning the making of a mock-up (PMU) and manipulating materials to explore one element of a possible solution (MANIP), followed by making a mock-up (MMU) and refining a mock-up (RMU) were anticipated to constitute the essence of the modelling step. Checking available resources and materials (ARM) and abandoning a current solution in order to explore a new solution (ABAN) were codes which emerged from the data. One dyad, having

Table 4

Time spent on the step "Generating Possible Solutions"

	Time(secs) *% of total time*				
Code	Dyad 1	Dyad 2	Dyad 3	Dyad 4	Dyad 5
GEN	40 *2.05*	49 *2.63*	24 *3.22*	95 *2.58*	168 *5.53*
DRAW	36 *1.85*	27 *1.45*	4 *0.54*	0 *0*	13 *0.43*
GEN/DRAW	37 *1.90*	61 *3.28*	46 *6.18*	0 *0*	51 *1.68*
GEN/MANIP	7 *0.36*	62 *3.33*	38 *5.10*	54 *1.68*	98 *3.23*
Totals	120 *6.16*	199 *10.69*	112 *15.04*	149 *4.05*	330 *10.87*

completed a mock-up, and concerned that they had not heeded the constraints described in the design brief, ("Oh, we never measured how much millimetres [of tape] we used", S8, lines 590-592) decided to build a replica in order to "see that it can be done again and that there's not just one that can be done" (S8, lines 602-604). Hence the code CMMU (making a copy of a mock-up) was added.

From Table 5 it is clear that subjects spent very little time planning the

Table 5

Time spent on the step "Modelling a Possible Solution"

Time (secs)
% of total time

Code	Dyad 1	Dyad 2	Dyad 3	Dyad 4	Dyad 5
PMU	0 *0*	0 *0*	5 *0.67*	164 *4.45*	25 *0.82*
MANIP	47 *2.41*	102 *5.48*	8 *1.07*	0 *0*	4 *0.13*
MMU	455 *23.34*	0 *0*	79 *10.60*	533 *14.45*	1021 *33.62*
RMU	418 *21.43*	0 *0*	9 *1.21*	699 *18.96*	708 *23.31*
ABAN	0 *0*	2 *0.11*	0 *0*	11 *0.30*	18 *0.59*
ARM	44 *7.39*	26 *1.40*	41 *5.50*	247 *6.70*	126 *4.15*
Totals	1064 *54.57*	130 *6.99*	142 *19.05*	1654 *44.86*	1902 *62.62*

sequence of steps in making a mock-up. Time spent planning a mock-up ranged from 0% to 4.45% of time on task. With one exception (Dyad 2) little time was spent manipulating materials to explore elements of a solution. The time dyads spent making a mock-up ranged from 0% to 33.62%, and the time refining a mock-up, that is, making ongoing and immediate design changes, ranged from 0% to 23.31%. Again, the idiosyncratic case is Dyad 2, which spent no time at all modelling a solution, but moved directly to making a prototype.

Worth noting also is the number of mock-ups, or different possible solutions to the problem, explored by each dyad. Dyad 2 made no mock-ups. Dyad 3 made one, Dyads 1 and 5 made three, and Dyad 4 made five. In this latter case four different solutions were explored and one of them was repeated, as discussed earlier.

The time dyads spent checking and organizing available resources and materials ranged from 1.40% to 7.39%. Deciding whether or not to abandon a current solution and try something different required between 0% and 0.59% of the time.

Building a Solution

While a prototype is usually "a full-size working model of a physical system" (Evans, 1992, p. 42), for the purposes of this study the term prototype was used to signify a "final model" of a design solution. As Kimbell et al. (1991) have pointed out "there is nothing particularly special about the 'final' prototype, for the moment it exists it becomes the focus for yet further refinement and is therefore but another extension of modelling activity" (p. 22).

Dyads spent between 11.22% and 57.88% of their time building a prototype. Table 6 shows that dyads spent very little time planning the production of a prototype (PPR), the range being 0% to 3.87%. Dyads 1 and 3 moved immediately from making a mock-up to making the prototype without any

Table 6

Time spent on the step "Building a Solution"

	Time (secs) *% of total time*				
Code	Dyad 1	Dyad 2	Dyad 3	Dyad 4	Dyad 5
PPR	0 *0*	72 *3.87*	0 *0*	12 *0.33*	31 *1.02*
MPR	185 *9.48*	381 *20.47*	95 *12.75*	195 *5.29*	311 *10.24*
IPPR	0 *0*	39 *2.1*	40 *5.37*	0 *0*	0 *0*
MODPR	34 *1.74*	585 *31.44*	129 *17.32*	636 *17.25*	0 *0*
Totals	219 *11.22*	1077 *57.88*	264 *35.44*	843 *22.87*	342 *11.26*

planning. Dyads 2, 4 and 5 spent minimal time on this part of the activity.

Once production of a prototype began (essentially replicating the selected mock-up) little time was spent explicitly identifying design problems (IPPR), but considerable time was spent modifying and improving the prototype (MODPR), that is, making design changes as making continued. The time dyads spent modifying a prototype ranged from 0% to 31.44% of time on task, but as will be discussed in detail in the next chapter, most of this time was spent attending to very minor technical changes; for example, retaping an element to make it more secure.

Evaluating

For the purpose of this study evaluating was used as an umbrella term to include testing, evaluating, and recording results. Testing was defined as the assessment of one or more elements of a possible solution as designing continued (TMU and TPR). Evaluating was defined as either making decisions while discussing an idea (EGEN) or a sketch (EDRAW), or the assessment of a complete solution in terms of the performance criteria contained in the design brief (EMU and EPR). After all, the critical question in evaluation is "Does the proposed solution meet all of the goals and conditions set by the problem?" Thus, after developing a solution the designer must turn attention back to the problem statement and check carefully to ensure that the solution satisfies it. So, for example, an episode during which subject S7 attempts unsuccessfully to make the base of a model tower stand and says "Maybe its not even or something on the bottom" (lines 860-861) was coded as testing one element as designing continues (TMU). Later on, when the same tower is complete and standing, an episode in which subject S8 begins to measure the height of the tower and says "There, it may not be as high as the other one because its sort of pushed down" (lines 1030-1032) was coded as evaluating the mock-up in terms of the design brief (EMU), since there is a clear verbal reference to and action supporting a performance criteria contained in the design brief, that is, the height of the tower is important and must be maximized.

In early models of the design process, evaluation was described as occurring as the final stage of the process. For example, in the design process model proposed by the Schools Council Design and Craft Project (1974), one of the earliest projects to survey design activities in secondary schools, "testing" was placed at the end and only at the end of the design process. Testing was defined as a "judgment of the solution in terms of the brief ..." (Schools Council, 1974, p. 2). This reflects the linear nature of early design process models.

As the iterative nature of designing has been increasingly reflected in the models, evaluation has been seen to occur continuously and repeatedly throughout. This fact is reflected in this study, where the percentage of time spent evaluating ranged from 12.44% to 24.67%.

From Table 7 it can be seen that subjects spent no time at all evaluating as they discussed possible solutions, and only one dyad made any attempt to evaluate a drawing.

Dyad 2 (idiosyncratic in a number of ways) and Dyad 3 spent little time testing and evaluating a mock-up (0% and 2.69% respectively), but considerable time testing and evaluating a prototype (16.71% and 19.73% respectively). Dyad 3 spent no time at all testing a prototype. In fact, they quickly replicated the mock-up and then, and only then, evaluated the prototype in terms of the design brief by counting the 30 seconds it was required to stand before measuring its height.

Dyads 4 and 5 spent considerably more time testing and evaluating both mock-ups and prototypes. This is partly explained by the fact that these two dyads investigated more possible solutions than the other dyads. Dyad 4 spent 12.68% of their time in the testing and evaluation of five mock-ups and 9.35% of their time testing and evaluating a prototype. Dyad 5 spent 11.19% of their time in the testing and evaluation of three mock-ups, but very little time (1.25%) testing and evaluating a prototype.

Table 7

Time spent on the step "Evaluating Solutions"

	Time (secs) *% of total time*				
Code	Dyad 1	Dyad 2	Dyad 3	Dyad 4	Dyad 5
EGEN	0	0	0	0	0
	0	*0*	*0*	*0*	*0*
EDRAW	0	40	0	0	0
	0	*2.15*	*0*	*0*	*0*
TMU	41	0	2	251	103
	2.1	*0*	*0.27*	*6.82*	*3.39*
EMU	213	0	18	216	237
	10.92	*0*	*2.42*	*5.86*	*7.80*
TPR	10	97	0	51	8
	0.51	*5.21*	*0*	*1.38*	*0.26*
EPR	166	214	147	294	30
	8.51	*11.50*	*19.73*	*7.97*	*0.99*
RRMU	0	0	0	64	0
	0	*0*	*0*	*1.74*	*0*
RRPR	0	11	12	33	0
	0	*0.59*	*1.61*	*0.90*	*0*
Totals	430	362	179	909	378
	22.04	*19.45*	*24.03*	*24.67*	*12.44*

Based on the review of literature subjects were anticipated to make some written record of the results of their designing, that is, the height of their tower. As can be seen from Table 7 only Dyad 4 recorded in written form the height of their mock-ups. However, Dyads 2, 3 and 4 recorded the height of their prototype.

Question 2. What design process do Grade 7 students, working in single-sex dyads, use to solve a technological problem?

The coding scheme developed for this study reflects the problem-solving nature of designing as described in the technology education literature. This literature, described in Chapter 2 and summarized in Figure 1, identifies a characteristic sequence of actions (Hayes, 1989) or steps in the design process: Finding the problem, understanding the problem, generating possible solutions, modelling a possible solution, building a solution, and evaluating a solution. Not all the steps identified and described in the literature are relevant to this study. The first step (finding the problem) is not relevant, since subjects were provided with the problem. Hence only the remaining five steps were used as a structure for the coding scheme.

What is not included in the theoretical models is an indication of the precise path through the steps followed by a young designer, nor the time devoted to each step. In this study both of these omissions are made evident. As described in Chapter 3 the actions of subjects were videotaped and the start time of each action recorded. This allowed for the calculation of the time, in seconds, spent by subjects on each step in the process. Additionally, the precise path through the steps, including frequent toing-and-froing between the steps, is made evident. These data allow for a detailed map of the path taken by a dyad through the design process to be drawn. The next five sections of this chapter describe the design process, that is, the sequence of actions, used by each of the five dyads which constituted the sample for this study.

Dyad 1 Map Analysis

The map showing the design process used by Dyad 1 (Figure 13) shows three distinct periods. The first (up to 8.5% of the time) shows subjects reading the design brief, drawing, and manipulating materials as they discuss a possible solution. The second period (from 8.5% to 62.7% of the time) shows subjects making, testing and refining a mock-up, leading to the production of a prototype, which is abandoned. This leads to the third period, (from 62.7% to the end) during which subjects make a second mock-up and then prototype.

After spending 49 seconds reading the design brief both subjects picked up a pencil and sheet of pink paper and began to sketch. At this point, reminded by the researcher that they should work as a team, S1 began to explain to S2 a solution. S2 responded by pointing out a constraint, which lead to a discussion of possibilities:

S2:	Can only use one sheet of paper.	175
S1:	Yeah, half ...	177
S2:	Fold it in half.	179
S1:	No, cut it in half.	181

S1 then continued to develop the idea by taking a sheet of pink paper and rolling it into a cylinder. S2 responded by saying:

S2:	Yeah, need more support on the	195
	bottom, so we need to cut a piece off	196
	.... sort of a base.	197

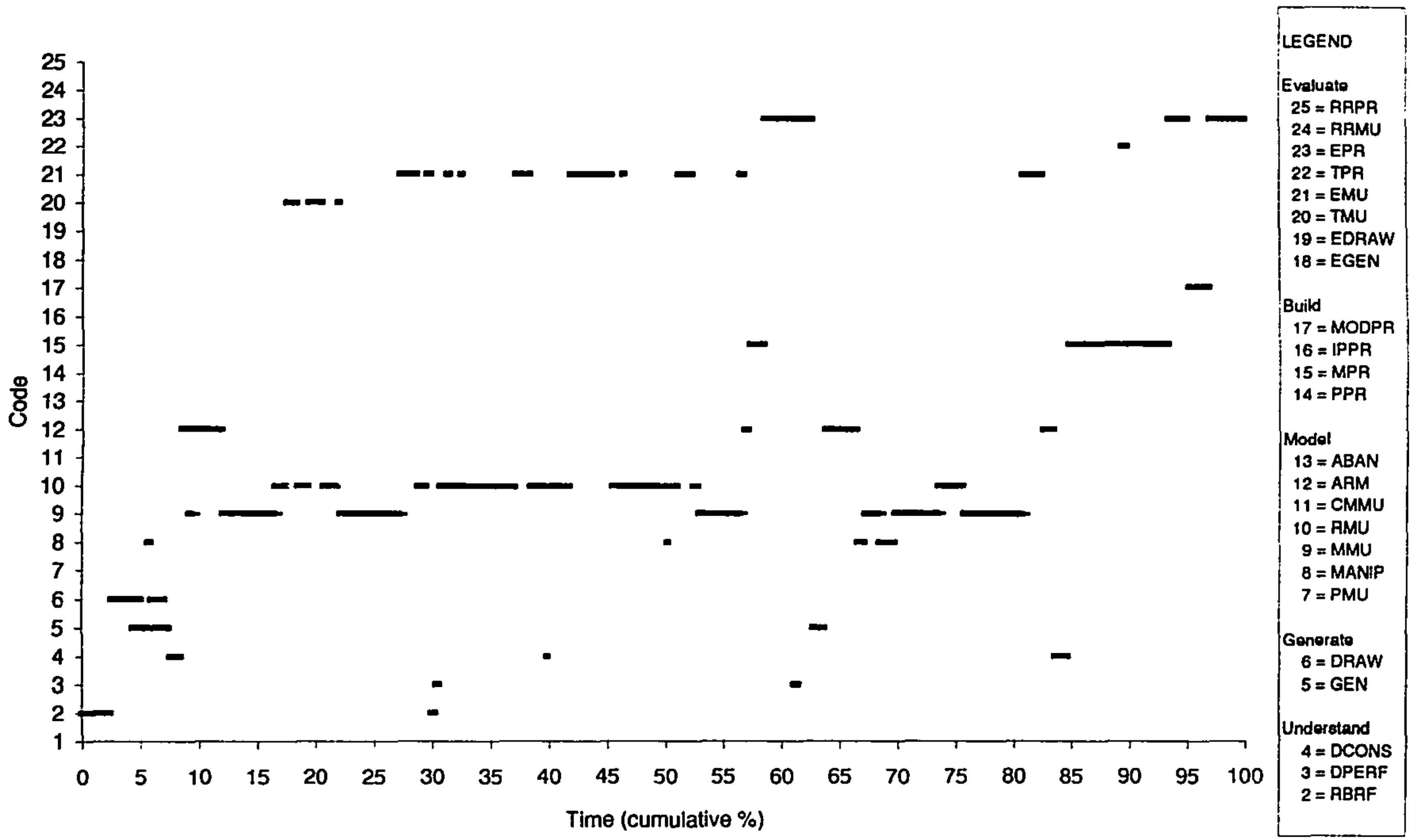


Figure 13. The design process used by Dyad 1

This solution appeared acceptable to both subjects and there followed a period during which they cut the paper into two, rolled and taped two cylinders and then attempted to join the two cylinders. There was a clear pattern of model-test-refine-test-model as activity continued.

Having made and joined the two cylinders S1 returned to the issue of a base:

S1:	Let's cut the bottom out, make sure	305
	it stands.	306

He then cut and bent tabs at the bottom edge of the tower, attempted unsuccessfully to stand the tower, modified the tabs and tested the tower once more. Continuing lack of success with standing the tower lead to S1 dismantling the two cylinders and attempting to stand just the lower half of the tower. Again there was a period of test-refine-test until the lower portion of the tower stood. S2 then took over, fitting the top section of the tower to the base. Repeated unsuccessful attempts to stand the tower lead S1 to use an eraser to anchor the base to the table top, but S2 reacted by picking up the design brief and reminding S1 of a constraint:

S2:	He said you couldn't tape it he	431
	said, look, say look.. where is	432
	it? You can't tape it down, see?	433
S1:	Can't tape it to the floor or	435
	anything else.	436

After further modification of the tabs and unsuccessful attempts to stand the tower S1 observed:

S1:	There's not enough weight at the	477
	bottom.	478

S1 now entered into a period of test-refine-test during which he made the tabs longer, tested the tower, made the tabs longer yet, tested the tower, and so on.

Finally S2 suggested that they sacrifice some height for stability:

S2:	We're going for the height, right.	525
	We'll just try to cut it down and	526
	see.	527

to which S1 responded:

S1:	Maybe we can fold it.	529

S2 insisted on his solution, leading to further discussion:

S2:	If we lose some of the height.	537
S1:	Yeah, shrink the thing down.	540
S2:	The base has to be bigger.	542

A further unsuccessful attempt to stand the tower lead S2 to pick up a new sheet of pink paper, roll and tape it into a cone, which stood for 30 seconds. He commented:

S2:	It's tall, it's free standing and it	577
	won't fall. It's not as tall, but it's	578
	tall, it's free-standing and it won't	579
	fall.	580

This appeared to satisfy both subjects, for S1 indicated to the researcher that they were "done". At the request of the researcher S1 measured the height of the tower (280 mm), which prompted the following comments from the subjects:

S1:	It's simple.	651
S2:	Not the most beautiful looking	653
	thing.	654
S1:	It's not that tall either.	656

At which point S2 said:

S2:	I think we'd like to do a bit more	674
	work on it.	675

S2 then began to dismantle the first prototype while S1 cut a sheet of pink paper into two and began to form a cone with one piece. There followed an extended period during which S2 made a cone for the lower section of the tower and S1 made a cylinder with the remaining paper for the top section.

In contrast to their earlier efforts subjects did not test at each stage of this modelling. Rather, they made the mock-up in its entirety, incorporating refinements as they worked through the construction. There was no obvious reference to testing or evaluation until this second mock-up was complete. Only upon completion did subjects evaluate the mock-up, decide that it was superior to the first and move immediately to making a second prototype.

Making a second prototype began with S1 disassembling the mock-up and then using the two pieces as a pattern for marking and cutting the white paper, from which they made the second prototype.

Making the second prototype followed the previous pattern of build-test-refine-test-build until their tower 425 mm high stood for the required 30 seconds.

Dyad 2 Map Analysis

Dyad 2 were the least successful in producing a prototype which met the performance criteria described in the design brief. Their tower was less elegant and considerably shorter (325 mm) than those designed and built by other dyads. While Dyad 2 did ultimately make a tower which stood for the required 30 seconds, this success appeared to be a result of luck rather than planning or thoughtful construction. This lack of success may be explained by a comment made by S4 after 15 minutes of trial-and-error:

S4:	I saw this in another class made	335
	with straws.	336

It appears this subject was attempting to replicate a solution made with a material with entirely different characteristics to the paper which they had been given. The problems arising from this misconception will become evident in the analysis of the problem-solving session which follows.

The map (Figure 14) shows that Dyad 2 began their problem-solving session with a period of discussion and sketching. S4 took the lead and described, using both a sketch and verbal description, a solution to S3:

S4:	Okay. We're going to cut it ...	163
	... we can tape and we can make	174
	a circle ... bend it.	175
S3:	Right.	177
S4:	And a little tape on the sides,	179
	and we, we combine it right here and	180
	keep on going round.	181

Both subjects put down their pencils, and S3 picked up the sheet of white paper. Neither subject seemed to have understood from their reading of the design brief that the pink paper was available for them to make a mock-up and that the white paper should be used only to make a prototype.

S3 picked up the scissors, and, unsure of the direction in which to cut the paper, began a discussion:

S3:	.... going this way?	187
S4:	I'm going this way or that way.	189
S3:	This is my way. This is your way.	191
S4:	You go this way.	194

At this point S3 cut off a strip of white paper, handed it to S4 who then bent and taped it into a cylinder. S4 then pointed to his sketch on pink paper, then pointed to the remaining white paper and instructed S3:

S4:	Start, start cutting strips out of	210
	this.	211

Simultaneously S4 was cutting and bending tabs at the base of the short cylinder in an effort to make it stand vertically.

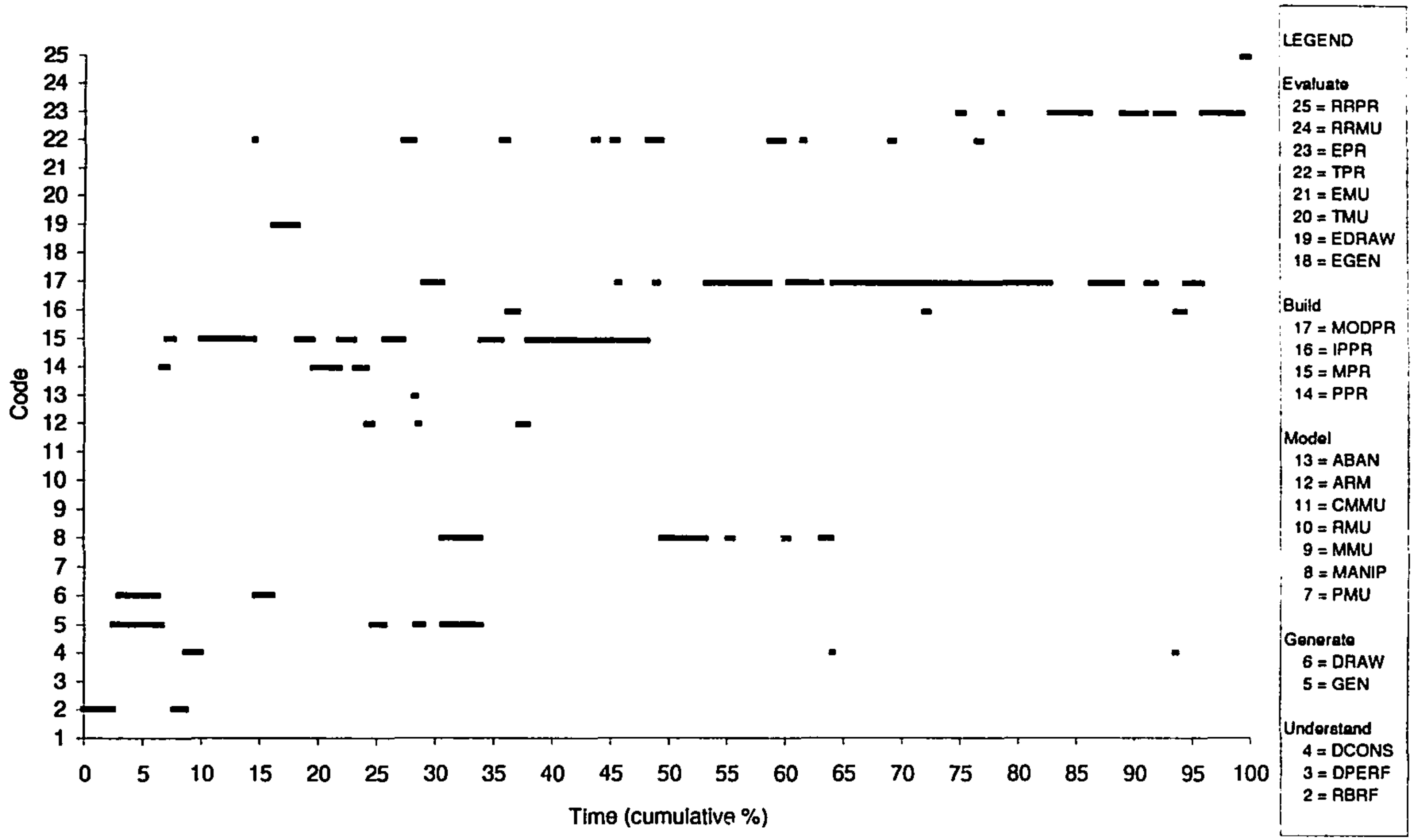


Figure 14. The design process used by Dyad 2

Having cut four narrow strips from the remaining white paper, S3 then began to tape them to the side of the base. When four had been joined subjects engaged in a discussion about the best way to join them at the top:

S4:	Are we going to join this?	264
S3:	Yeah.	267
S4:	What do you want to do? Put it,	269
	this together like that?	270
S3:	Okay.	272
S4:	We'll make a cone, tape it on the	280
	outside.	281

S4, having taped the four strips at the top, attempted unsuccessfully to make the tower stand. Neither subject recognized that the strips of paper were too flimsy to support their own mass. However, by bending the strips they did ultimately remain vertical, at which point S4 began to cut more narrow strips of white paper and suggested that they add a second set of strips to the top of the tower:

S4:	Use the tape see what we can do	307
	right. Make another one go up	308
	like that.	309

S4 then began to tape the new strips to the top of the tower, which prompted S3 to observe that the structure looked flimsy. When a second set of four strips were attached to the tower an unsuccessful attempt to stand the tower (evaluation) lead S3 to observe:

S3:	Its going to be too wobbly.	440

and then later, after several more unsuccessful attempts:

S3:	How are we going to do it?	454
	I don't think it will stand up.	463
	Its gonna fall.	464

S3 then suggested a modification. He picked up a section of the remaining white paper, pointed to the base of the tower, and then wrapped the white paper around the base of the tower. S4 agreed with this modification and taped the piece into position.

There now followed a series of episodes during which both subjects bent, squeezed, and modified the shape of the tower in an effort to make it sufficiently rigid to stand for the requisite 30 seconds. Both subjects suggested a variety of modifications:

S4:	Just bend it.	573
S3:	Squash it.	594
S4:	... wrap a piece of paper around.	606
S3:	Tape at the bottom ...	626
S4:	Bend it this way.	651
S3:	Push it down.	664
S3:	Make the base bigger.	693
S3:	Crush it like that so it	740
	straightens it out.	741
S3:	Do you want to make more slits in	749
	it?	750

At 36 minutes, 44 seconds the tower stood for 30 seconds, following which S4 measured and recorded the height (325 mm). Subjects agreed that they had solved the problem:

S3:	We're done.	784
S4:	Yep.	785

Dyad 3 Map Analysis

The map representing the design process used by Dyad 3 (Figure 15) most closely reflects the theoretical map in Figure 6. There is an obvious linear progression through the designing, beginning with a period during which subjects discussed and sketched possible solutions. This is followed by the making of a model, which in turn leads to the making and evaluation of a prototype.

Dyad 3 spent 44 seconds reading the design brief. This was immediately

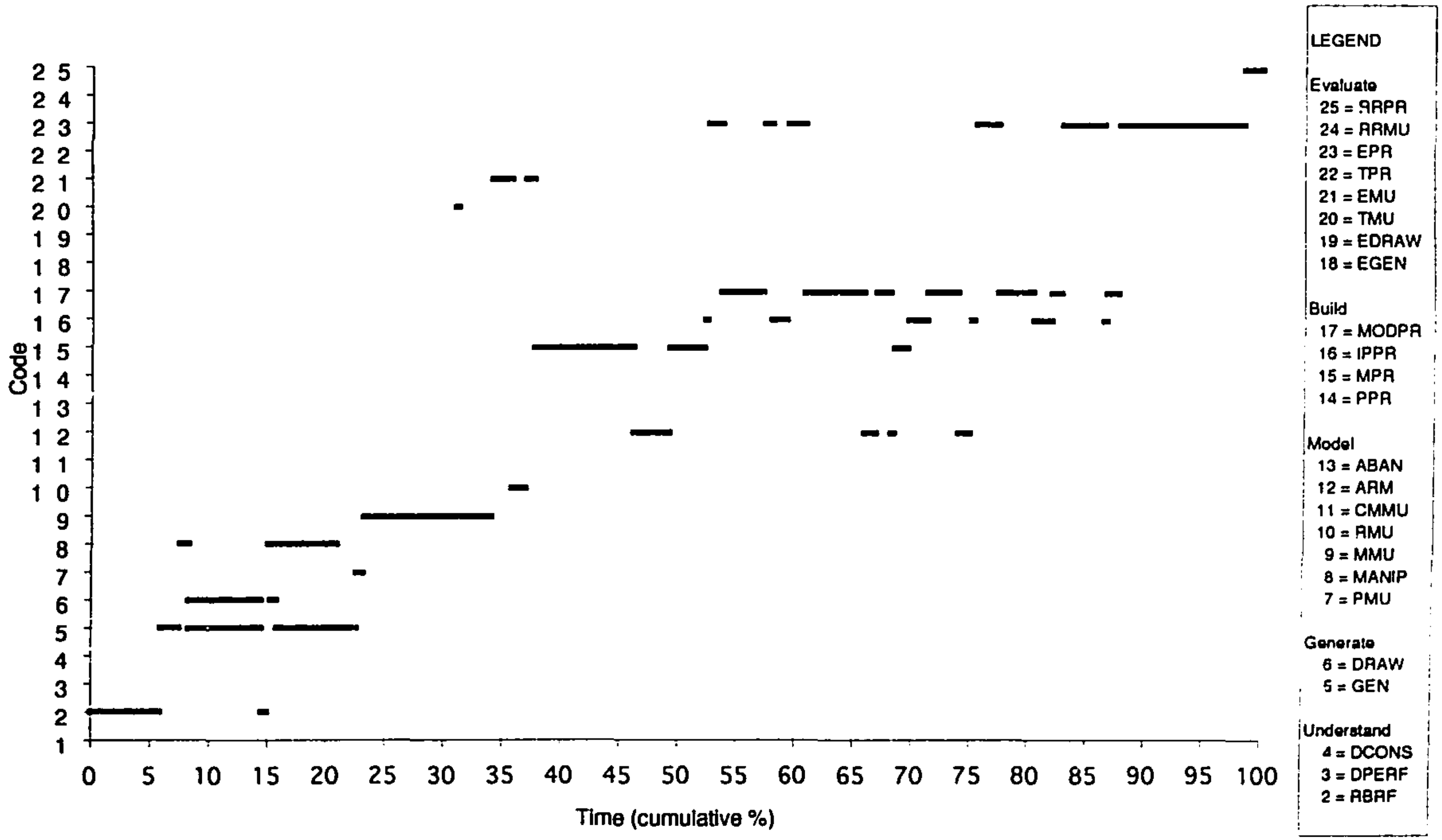


Figure 15. The design process used by Dyad 3

followed by a period during which the subjects discussed, sketched and modelled a possible solution. S6 began the discussion by asking:

S6:	Okay, um, what kind of structure?	145

to which S5 replied:

S5:	Okay now. We're going to need a	147
	solid base.	148

S6 picked up the sheet of white paper and rolled it into a cylinder, to which S5 reacted by picking up a piece of pink paper and pencil and saying:

S5:	That's not quite tall enough. If	154
	we could, let's work on the drawing	155
	first, Okay.	156

There followed a short period when both subjects were sketching, but S5 soon returned to manipulating materials in order to explore a possible solution. S5, rolling into a cone the piece of paper on which he had been sketching, commented:

S5:	A cone would be best.	194

to which S6 responded:

S6:	How about if we make it	202
	rectangular?	203

S5 pointed out that a rectangle would not be as tall as the cylinder he made earlier, but then he suggested cutting the paper in half, which prompted the following discussion:

S5:	Wait, wait, wait. Um, if we cut	211
	this in half, and we tighten one a	212
	little tighter than the other. And	213
	then we could put the tape around it.	214
S6:	Yeah, and then how do we make it	217
	stand?	218
S5:	Well, let's see. If we cut it	220
	into the cone, which is this ...	221
S6:	What happens if it doesn't stand?	223
S6:	If it doesn't stand we have a	225

	problem.	226
S5:	We can make little notches at the bottom and they can sort of stand.	228 229

This appeared to both subjects to be a promising solution and there followed a model-test-refine-model session during which the subjects divided one piece of pink paper lengthways, rolled both pieces into cylinders, joined them and made the tower stand for 30 seconds.

Having successfully stood the mock-up for 30 seconds S6 immediately picked up the sheet of white paper and began to replicate the mock-up. There was no pause to consider whether or not the mock-up could be improved or whether an alternative solution might be superior.

Once started on the making of a prototype the build-test-refine-build pattern emerged. This continued until subjects evaluated the prototype by timing the 30 seconds it was required to stand. Their problem-solving session ended with S6 recording the height of the prototype (527 mm) on a sheet of paper.

Dyad 4 Map Analysis

The problem-solving session with Dyad 4 began with one of the subjects (S8) reading the design brief out loud to her partner (Figure 16). Having completed this she immediately picked up the piece of white paper, hesitated, reread the design brief, exchanged the white paper for a sheet of pink paper and said:

S8:	Okay, I'm going to try it.	127

S8 then rolled the paper into a cylinder, taped the seam, stood the cylinder and measured, using imperial, its height. Having agreed that it was eleven inches tall there followed a discussion as to how the height could be increased:

S8:	Um, how else could we ... we can tape it.	165 166

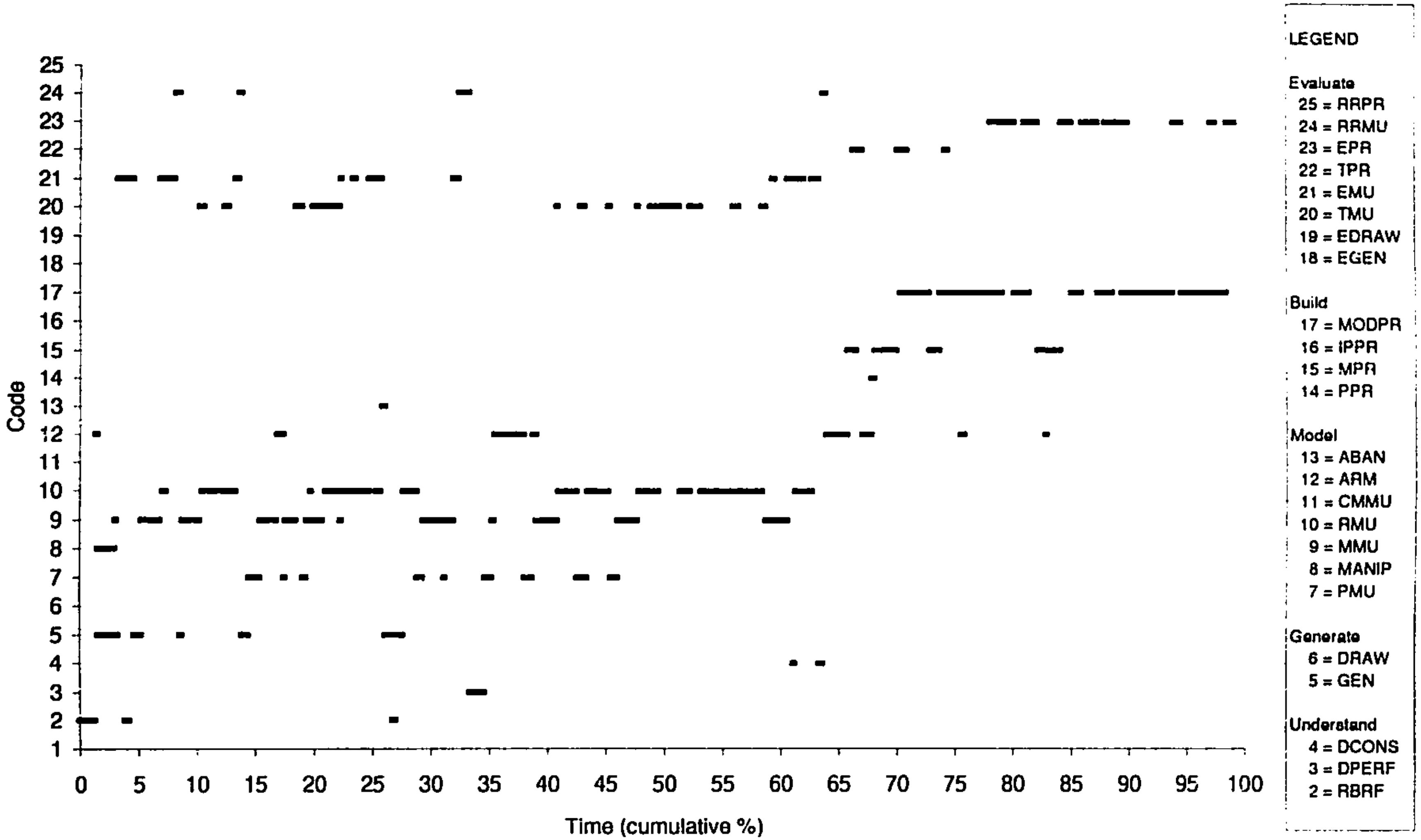


Figure 16. The design process used by Dyad 4

S7:	Turn it up or something.	168
S8:	Can you, we could cut it.	170
S7:	Here um.	172
S8:	You could cut it and then roll	174
	half of it and roll the other half and	175
	stick it together to make it tall.	176
S7:	Oh yeah, try it.	178

Subjects then cut a sheet of pink paper across its width, rolled and taped two 220 mm (8 1/2") long cylinders and combined them into a tower. When the tower failed to stand the first time S8 declared:

S8:	I just got to make it even on the	201
	bottom.	202

which she proceeded to do using scissors. There followed a period when both subjects were engaged in a model-test-refine-test strategy until, at the third attempt, the tower stood for the requisite time. Subjects then engaged in a period of evaluation:

S7:	Yeah, measure this one.	210
S8:	Go ahead.	212
S7:	Um, 15 and 1/2 inches I think.	214

This was followed immediately by a suggestion from S7 that they try to improve the height:

S7:	So try and make something bigger	215
	than, this is the biggest.	216

S8 meanwhile recorded the height of the tower using imperial measurement (15 1/2 inches) on a piece of pink paper. She also remembered that she had not recorded the height of the first mock-up and so wrote this down. She then immediately began to discuss improving the solution, which prompted S7 to suggest that they use the paper lengthways:

S8:	That's what we have, okay, how	230
	else?	231
S7:	Try to make them, um, cut it that	233
	way and we can roll it that way, the	234

	same thing.	235
S8:	The same thing?	237
S7:	Yeah and then it will be a little	239
	taller than that one.	240

Subjects then engaged in a period of make-test-refine-test-make as they built a tower comprised of two cylinders, each 280 mm long. This resulted in a successful solution, which was evaluated by S7, who then recorded the height (21 inches) on paper. There followed immediately a further discussion about ways to increase the height:

S7:	What else?	291
S8:	Okay, um, we could cut it in three	293
	which would make it even smaller and	294
	skinnier.	295
S7:	Four, no. Okay let's try that.	297

There followed the first attempt to plan the making of a solution, when subjects discussed the most effective direction in which to cut the paper:

S7:	... try it that way	307
	'cause then it will be a lot taller.	308
S8:	Yeah, I'm going to measure it ...	310

S8 used a ruler to divide a sheet of paper into three equal strips before cutting, rolling, taping and joining them. This making of a fourth mock-up was characterized by a series of model-test-refine-test episodes in an attempt to make a three-part tower stand. Throughout, both subjects suggested ways to improve the stability of the tower:

S7:	We can cut this and make it a flat	390
	bottom or something.	391
S8:	Um, we need some more weight on	413
	this side ... so stick a bunch of	414
	tape on it.	415
S8:	We'll just roll it some more.	417

After exploring a number of unsuccessful modifications S7 finally became exasperated and said:

S7:	Yeah. Guess you have to stick	457
	with two.	458

At this point both subjects sat still, apparently thinking about the problem. After a few seconds, S8 began to read the design brief and suggested that they could modify the third mock-up by cutting a small amount off the top cylinder and rerolling it in the opposite direction to make a smaller cylinder which could be fitted to the top edge. Once again subjects engaged in a model-test-refine-test strategy until a successful solution was completed. S8 took charge of evaluating the solution by measuring the height (23 1/2 inches) and recording it on paper.

Following this S8 picked up the design brief and began to evaluate the modified third mock-up, which lead to the realization that they had not abided by all of the constraints:

S8:	Now, do we use everything we	577
	could, okay. Tower must be free	578
	standing it cannot be taped to the	579
	floor or anything else. When you	580
	have finished the tower must stand	581
	for 30 seconds before having its	582
	height measured. Okay so it can	583
	stand, um, its not taped to the	584
	floor.	585
S7:	Or the table.	587
S8:	The table, um, okay and 100	589
	millimetres of clear tape. Oh, we	590
	never measured how much millimetres	591
	we used.	592

S7 responded by suggesting that they remake the third mock-up

S7:	Do it over.	598
S8:	We can, yeah, we can do it over	600
	again. Okay and use as less tape as	601
	we need. Just to see that it can be	602
	done again ...	603

Subjects spent the next 21 minutes, 26 seconds replicating the modified version of the third mock-up. Once again this period of time was characterized by a series of model-test-refine-test episodes.

Upon successful completion of this replica S8 stated that they must now make a prototype:

S8:	Now we have to do it with	1077
	the white paper.	1078

Building a prototype began in a more planned way as S8 measured off and cut 100 mm of clear tape, which she then cut into 10 smaller strips, sticking them to the edge of the table:

S8:	So just as you need them you just	1107
	have to rip off a little one, okay.	1108

Subjects spent the remainder of their time (21 minute, 02 seconds) replicating the modified third mock-up using the white paper. Subjects' actions were characterized by a series of build-test-refine-test episodes. They began by making and testing the lower cylinder, ensuring that the seam was well taped and that the cylinder stood for 30 seconds. The second cylinder was then constructed, joined to the base and the entire structure tested. When it failed to stand S8 said:

S8:	It's too shaky on the bottom.	1176

and proceeded to trim the bottom edge of the lower cylinder. S7 suggested:

S7:	Fold it in half like you did	1178
	before so it will be even.	1179

S8 responded by pointing to the bottom edge of the tower and said:

S8:	This isn't straight.	1188

and attempted to once more trim the bottom edge of the base. This test-refine-test pattern continued until both cylinders were joined and would stand. S8 then cut off the top 25 mm section of the tower, handed it to S7 who rerolled and taped it into a small diameter cylinder ready for S8 to affix it to the top of the tower. There followed a lengthy period of trial-and-error in which both subjects made minor adjustments to the tower in order to make it stand. Both subjects suggested modifications:

S8:	Ah, if we made it square it will	1294
	stay.	1295
S8:	We need crisp corners.	1314
S8:	Maybe if we put a flat thing on	1321
	the bottom.	1322
S7:	Just cut the whole bottom off ...	1388
S7:	Try folding this part right there ...	1400

Throughout this period both subjects were constantly making small adjustments to the tower in an effort to make it stand. Much time was spent retaping seams or adding additional tape in an effort to balance the tower. At the 73 minutes, 01 seconds time the tower stood, and S8 commented:

S8:	It looks pretty bad but its	1446
	standing.	1447

S7 measured the height of the tower

S7:	22 (inches)	1455

which S8 converted to metric:

S8:	Equals, equals 56, 55.9	1461
	centimetres. Which equals 559	1462
	millimetres.	1463

Interestingly, Dyad 4 did not time the 30 seconds that the tower was required to stand.

The design process used by Dyad 4 (Figure 16) is different from previous dyads in a number of ways. First, it is clearly more complex than any of the preceding dyads (which in part explains the fact that Dyad 4 spent the most time, 74 minutes 07 seconds, on the task). Second, Dyad 4 developed four quite different solutions to the problem. Third, they replicated one of these in order to confirm that it can be made using the available materials. Fourth, at no point did either subject make any attempt to solve the problem by sketching a solution. They either discussed a solution or manipulated materials and modelled a solution. Yet unlike other dyads they were conscientious about recording the test results for each solution.

Dyad 5 Map Analysis

What is immediately obvious from looking at the map of the design process used by Dyad 5 is that it contains four distinct episodes: the first three each represent separate attempts at a solution to the problem, and the fourth the making of a prototype (Figure 17).

The map shows that subjects began the designing session by reading the design brief. They then discussed the problem and a possible solution, spent a few moments sketching, but returned almost immediately to discussing a solution while S10 simultaneously rolled a sheet of paper into a cylinder to illustrate the solution she had in mind.

S10:	... making a pentagon. Divide it up like in strips or ...	187 188

an idea which is picked up by subject S9:

S9:	And then put them all together.	190

S9 suggested a different solution when she then folded the paper in half length ways, stood it on the table and asked:

S9:	Can it be higher than this paper? Cut it in half and then try and stick it up.	196 197 198

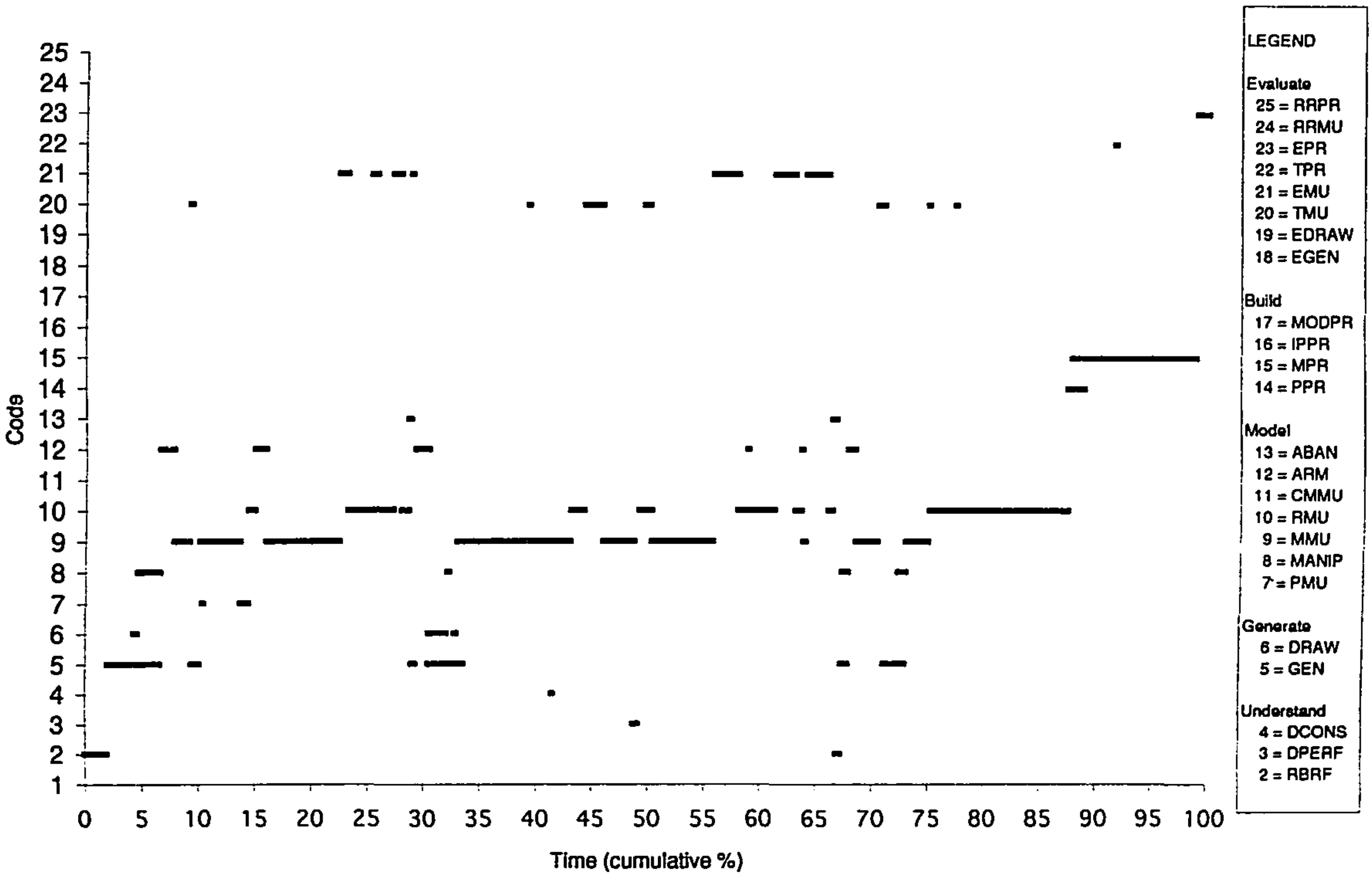


Figure 17. The design process used by Dyad 5

S10 took the idea further, suggesting that they cut the paper into strips, roll one strip into a cylinder as a base and then tape the strips to the base. They agreed that it was a possible solution and began to make the mock-up.

There was very little evaluation at this stage. Subjects continued to make the mock-up until reasonably well developed using a strategy of model-test-refine-model which has been evident in previous dyads. This they continued to do until it became obvious to them that the solution was not going to be successful, and at time 20 minutes, 26 seconds subject S10 said "Let's do something different".

Subjects then began to discuss an entirely new solution to the problem. They agreed that the tower needed a base but that it must be bigger and sturdier:

S10:	Okay. Definitely need a base.	525

and

S10:	a bigger base. More sturdy.	529

to which S9 agreed.

There followed a brainstorming session during which subjects threw out a series of ideas, each piggybacking on the previous idea. It began with S10 asking:

S10:	Okay then how do you want, how	543
	should we have the tall part?	544

to which S9 replied:

S9:	Would a tree work? Like if we	546
	took like something like this and just	547
	rolled it and then took other branches	548
	or something.	549

This lead S10 to suggest:

S10:	What if we made yeah, little rolls	553

and made it in a teepee style? 554

to which S9 replied:

S9: Yeah, like make some rolls 558
bigger than others. Let's try that. 559

This prompted S10 to note that a base was not needed:

S10: We don't even need the base. 567
Everything will be leaning on each 568
other. 569

At this point subjects began to cut a series of strips which they rolled into cylinders. Once again they engaged in a pattern of model-test-refine-test until this solution was complete. However despite a number of refinements, including ties around the tripod legs and cutting tabs at the bottom edge of each leg the tower would not stand for the required 30 seconds and so it was abandoned.

At this point subject S10, who tended to be the "ideas" person in the dyad, reread the design brief, looked at the first mock-up and said:

S10: What about something similar, 832
except ... I'm going to do a spiral 833
thing and I'm going to do a base. 834

Subject S9 appeared to catch onto the idea and suggested:

S9: Do you know how those card things, 854
you know how they build big castles 855
out of cards? 856

S10 then picked up a sheet of paper, cut off a strip and rolled it into a cylinder which S9 taped. Standing the cylinder on the table, S10 then said:

S10: What if we 863
added little pieces of paper at the 866
top? 867

S9 remembered the difficulties experienced with the first mock-up:

S9: You need a base around the bottom 869

if you're going to put all that weight 870
at the top. 871

S10 then cut a narrow strip, folded and taped it into a ring, which she taped as a base to the taller cylinder.

Subjects then engaged in another session of model-test-refine-model as they continued to make a tower consisting of stacked cylinders. This third session was characterized by a great deal of trial-and-error. Subjects completed a section of the tower, paused, reflected until one of them suggested a modification to increase the height. For example, S10 held a flat piece of paper on top of the cylinder and said:

S10: Try like a roof ... 893

to which subject S9 replied:

S9: ... make triangles. 895

Subjects continued to work in this way until a successful tower consisting of a series of stacked cylinders was completed, at which point S10 instructed her partner to begin making the prototype:

S10: Start cutting this stuff out of 948
.... white paper. 949

Subjects then discussed how they made the parts of the mock-up and then began to replicate their third mock-up in order to make the prototype.

Very little time was spent testing or evaluating the prototype. In fact not until the prototype was complete did subjects test it to determine whether or not it would stand. However, having done so, they proceeded to time the 30 seconds and then measured the height of the tower (550 mm). They made no attempt to record the height on paper.

Question 3. In what sequence do students employ steps of the design process?

Chapter 3 described how a coding scheme consisting of 24 codes, grouped into the five steps which underlie theoretical models of the design process (understanding the problem, generating possible solutions, modelling a possible solution, building a solution, and evaluation), was developed to analyze the design process used by subjects as they solved a technological problem.

This section of the chapter provides an analysis of the sequence in which subjects in this study employed the five steps of the design process. This analysis first requires, for each dyad, reference to the sequence of individual codes (Appendix J, Column 1) and secondly the translation of this sequence of individual codes into a sequence of steps (Appendix L). For example, all instances of the codes RBRF (reading the design brief), DPERF (discussing/referring to performance criteria), and DCONS (discussing/referring to constraints) were recoded as Understand (understanding the problem). A complete list of the steps and related codes is provided in Appendix I.

The recoded data was then mapped to provide a visual representation of the sequence in which subjects in a dyad employed steps of the theoretical models of the design process (Figures 18-22).

The sequence of steps employed by Dyad 1

Figure 18 shows the sequence in which Dyad 1 employed elements of theoretical models of the design process. The map shows quite clearly the dominance of modelling throughout the entire period when subjects were developing a solution. Equally clear is the iterative relationship between

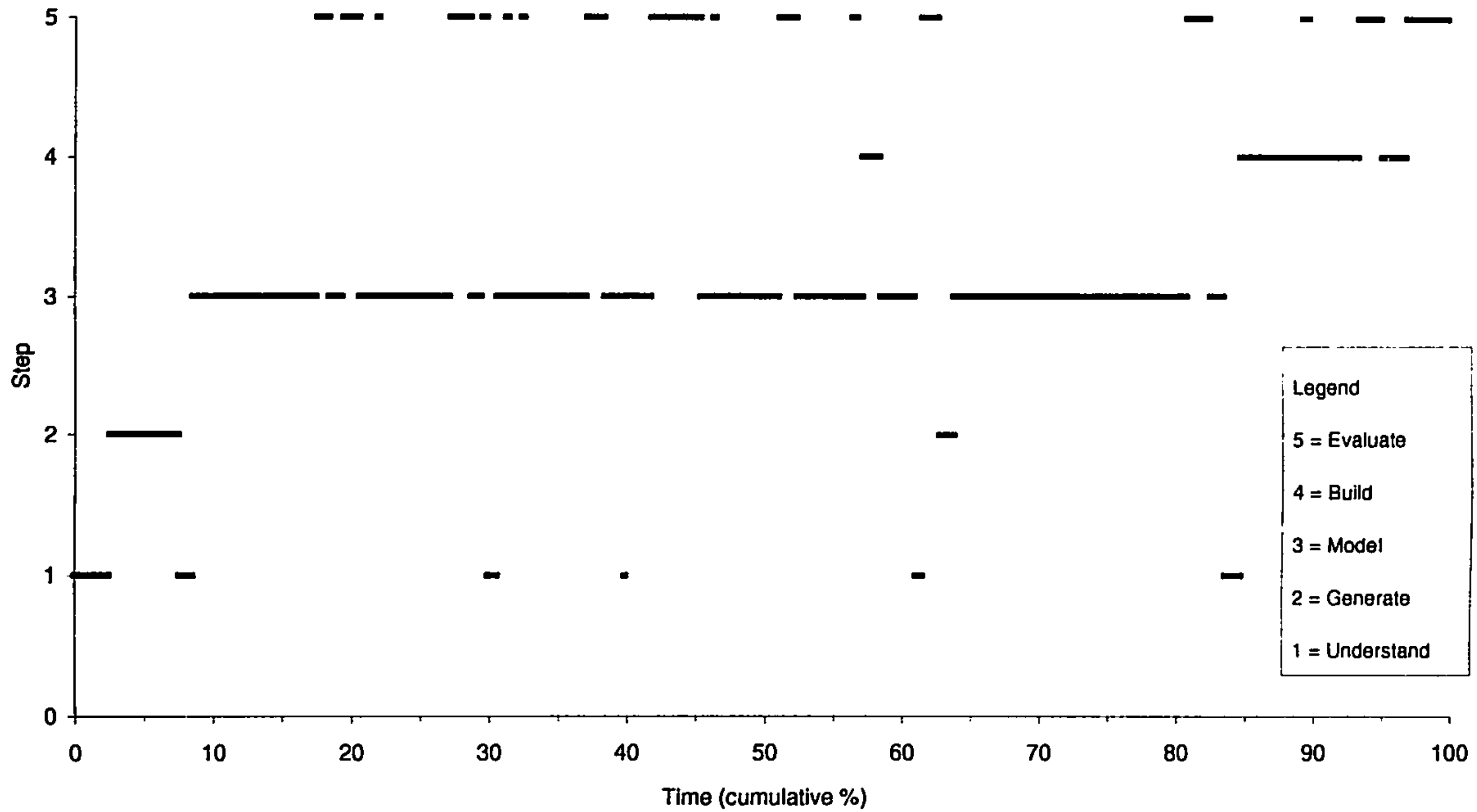


Figure 18. Sequence of steps employed by dyad 1

evaluating and modelling. Constant evaluating is also evident as subjects build a prototype. The map also shows how little time was spent at the beginning developing a solution by discussion or drawing and how quickly subjects moved to modelling in three-dimensional materials.

Subjects began by reading the design brief (Understand) followed by a period during which they generated a possible solution. This step involved subjects alternately discussing possible solutions or simultaneously discussing and drawing or discussing and manipulating materials. S2 then referred back to the design brief (Understand) and then both subjects began to model a possible solution. This period of modelling was characterized by a lengthy sequence of alternately modelling and evaluating the mock-up.

After a brief reference by both subjects to the design brief (Understand), subjects again engaged in a period of alternately modelling and evaluating a mock-up. This continued until both subjects agreed that the mock-up was complete. They then made a prototype (Build) and evaluate, that is, measured the height of, the prototype.

At this point, having apparently completed the task, subjects were asked by the researcher if, in fact, they were finished. To this S2 replied:

S2:	I think we'd like to do a bit more	674
	work on it.	675

Both subjects then began a discussion of alternative possible solutions (Generate), which led to a further period of modelling a possible solution. Very little evaluation occurred during the making of this second mock-up. Once completed, the second mock-up was evaluated, followed by a check of the resources available and reference back to the design brief (Understand). Satisfied with their second solution both subjects turned to making a second prototype (Build). This last period was again characterized by a sequence of alternately building and evaluating until subjects declared that the task was complete. At this point subjects measured the height of the tower (425 millimetres) but did not record the result.

The Sequence of Steps Employed by Dyad 2

As was noted earlier in this chapter Dyad 2 were idiosyncratic in that unlike all other subjects they did not model a possible solution before building a prototype. This is shown in Figure 19 where building can be seen as the predominant activity. The only instances of modelling occurred when subjects checked available resources and materials or when they abandoned a prototype. Also evident is the consistency and frequency of evaluating.

After reading the design brief (Understand) they spent a very short time discussing and drawing a possible solution (Generate). S4 then reread the design brief (Understand) and measured off the permitted amount of tape (Model). Subjects then moved directly to building a solution using the white paper, that is, making a prototype. This was followed by a brief period of testing (Evaluate), modifying and then discussing a drawing (Generate), before a return to making a prototype (Build).

There followed a period of alternately planning and making the prototype (Build). S4 referred to the amount of tape remaining which lead both subjects to suspend building and return to a discussion of the solution (Generate). This was followed by another period of building and evaluating. The tower did not stand for the required 30 seconds and so the solution was abandoned as S4 pushed it to one side. S3 immediately retrieved the tower, which prompted both subjects to discuss ways to improve their solution (Generate):

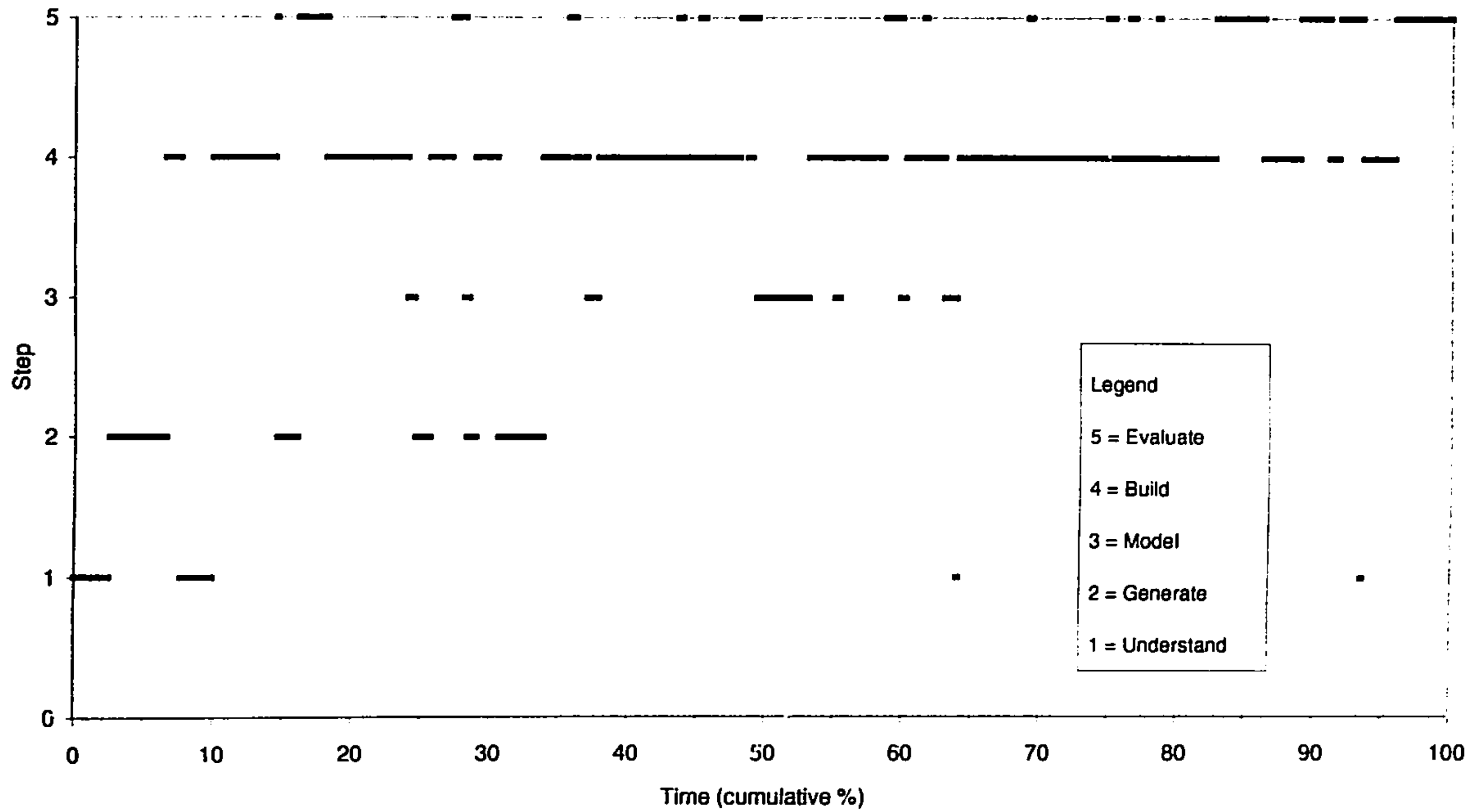


Figure 19. Sequence of steps employed by dyad 2

S4:	Okay. Now what?	299
S3:	Use the pencil.	301
S4:	Is this our paper too?	303
S3:	Yeah.	305
S4:	Use the tape see what we can	307
	do right. Make another one	308
	go up like that.	309

S4 referred back to his original sketch but did not make changes. He picked up the remaining white paper and began to cut more strips (Build). There followed a discussion about the number of strips required, indicating that subjects intend to modify the existing prototype (Build):

S4:	How much will you need?	320
S3:	Four	322
S4:	Four again?	324
S3:	Yep.	326

S4 then lead a discussion while simultaneously demonstrating ways in which the additional strips might be fastened to the top of the tower (Generate). This was accepted by S3 and both subjects engaged in a period of alternately building and evaluating.

Following an unsuccessful test of the prototype S3 commented:

S3:	I don't think it will stand up.	463
	Its gonna fall.	464

He then picked up one of the two remaining strips of white paper and suggested a variety of modifications to the prototype in an attempt to increase its rigidity (Model). Finally subjects agreed to tape an additional strip of paper to the base of the tower (Build). This was followed by S3 holding the last piece of paper around the top of the tower (Model) and suggesting:

S3:	Put it up there.	508

S4 ignored this as he continued to affix with tape the additional strip to the base of the tower (Build). Having completed this successfully there followed a period when the subjects engaged in alternately squashing and bending the tower (Build) and attempting to make it stand (Evaluate). Finally the tower stood and S3 looked at a clock on the wall and began to time the required 30 seconds (Evaluate). At the end of the 30 seconds S4 picked up a tape and measured the height of the tower (325 millimetres). This he told to both his partner and the researcher before writing it on a piece of paper (Evaluate).

The Sequence of Steps Employed by Dyad 3

The design process employed by Dyad 3 (Figure 20) most closely approximates the linear models described in the technology education literature and adopted as a theoretical model for this study (Figure 11). There is a simple linear progression from understanding the problem to generating a solution. This leads to a period of modelling, followed by building and evaluating a solution. Evaluation does occur intermittently throughout the process, but clearly not to the same extent as was seen with Dyads 1 and 2.

The subjects (S5 and S6) began by reading the design brief (Understand). They then spent very little time discussing and drawing possible solutions (Generate), before S5 suggested to S6 (who had picked up the sheet of white paper) that they should model a solution before building a prototype:

S5:	Before we chop that up I think we	235
	should test it out with some of this	236
	stuff.	237

Subjects soon settled for their first proposed solution, two identical cylinders joined atop one another. This took subjects very little time to model successfully. However this period was characterized by subjects alternately modelling and evaluating.

Having successfully stood the mock-up subjects turned immediately to

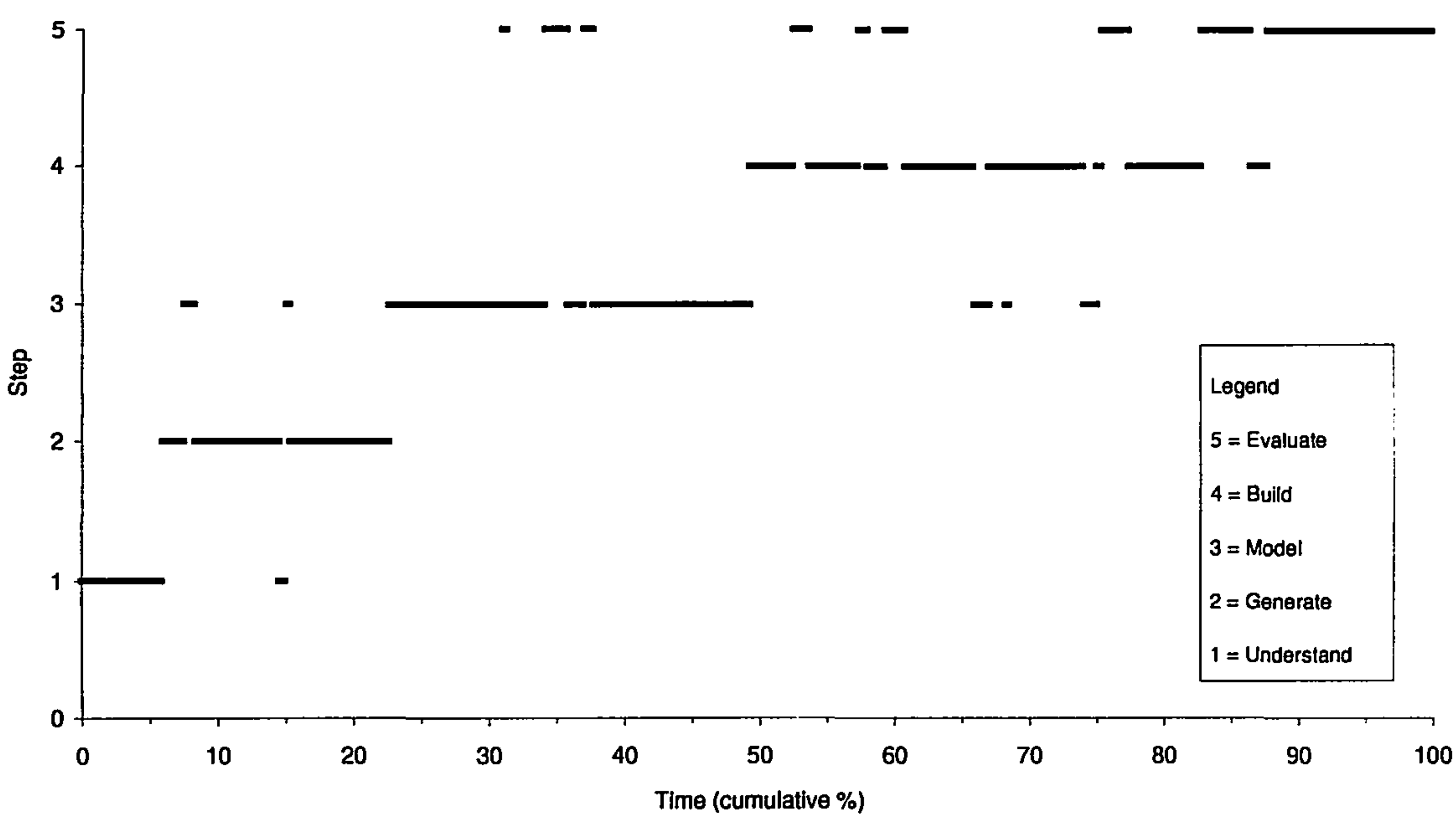


Figure 20. Sequence of steps employed by dyad 3

making a prototype (Build). This period was characterized by a build-evaluate-build iteration. S6 completed the task by measuring and recording on paper (Evaluate) the height of the tower (527 millimetres).

The Sequence of Steps Employed by Dyad 4

Figure 21 shows that Dyad 4, like the three previous dyads, spent very little time generating a solution by drawing or discussion, but moved very quickly to modelling a solution. Equally striking is the amount of time Dyad 4 spent evaluating, both while modelling and building.

After reading the design brief (Understand) Dyad 4 quickly generated, modelled and evaluated a solution. They then discussed a second solution (Generate) which was again quickly modelled and evaluated. A further discussion (Generate) lead to a third solution, which was modelled and evaluated. This evaluation occurred constantly throughout the construction.

A fourth solution was then proposed (Generate) which took a considerable time to model. This period was again characterized by a model-evaluate-model iteration. This fourth solution was unsuccessful in that subjects could not get it to stand for the required 30 seconds, and so it was abandoned.

At this point the subjects returned to their third mock-up and decided to modify its design. This period was again characterized by a model-evaluate-model sequence. At the successful completion of this stage, S8 reread the design brief and realized that they had exceeded one of the constraints (a maximum of 100 millimetres of clear tape). At this point subjects decided to repeat the third mock-up. Again this period is characterized by a model-evaluate-model sequence.

Successful completion of this fifth mock-up lead the subjects to begin

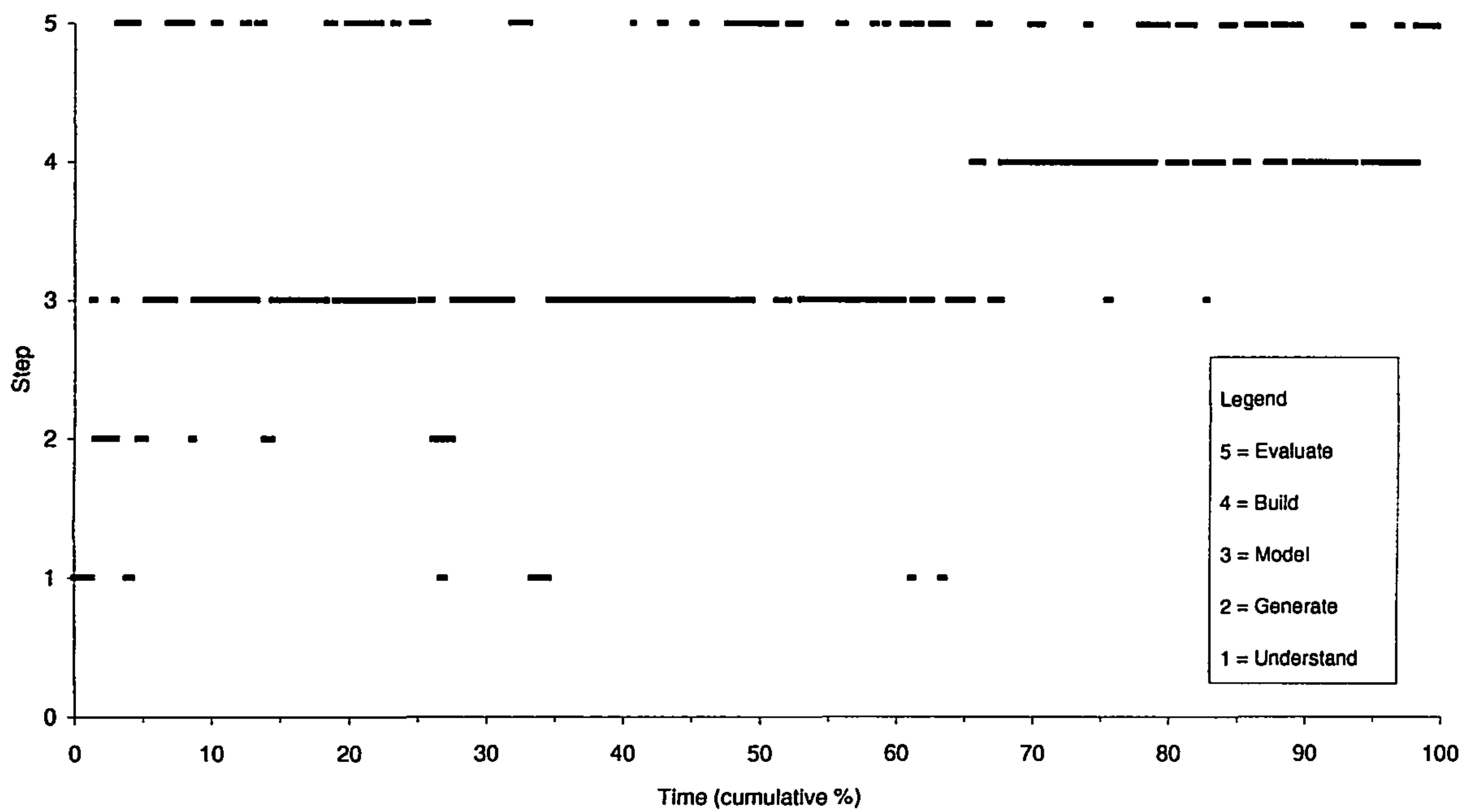


Figure 21. Sequence of steps employed by dyad 4

construction of a prototype. This entire period consisted of a build-evaluate-build sequence until eventually the prototype stood for the required 30 seconds. At this stage S8 measured the height of the tower (550 millimetres) and recorded the result on a piece of paper (Evaluating).

The Sequence of Steps Employed by Dyad 5

The most striking aspect of Figure 22, which shows the sequence of elements employed by Dyad 5, is the very large proportion of their time devoted to modelling. Once again it is clear that subjects spent very little time generating solutions either by drawing and discussion but moved very quickly to modelling, that is, using three-dimensional materials to develop their ideas. It is also clear that Dyad 5 evaluated throughout the time that they were modelling three different solutions. What is also striking is the relatively short amount of time devoted to building a prototype.

Subjects S9 and S10 began by reading the design brief (Understand). They then spent a short time discussing and drawing possible solutions (Generate) before modelling their first mock-up. Unlike other dyads subjects took time to plan each stage of this modelling. While modelling subjects were constantly evaluating.

After a number of unsuccessful attempts to make the tower stand S10 suggested:

S10:	Let's do something different.	496

S9 agreed with this and their first mock-up was abandoned. While S10 picked up a new sheet of pink paper, S9 suggested:

S9:	You know what? We should try	513
	using the minimum amount of tape when	514
	we build our practice one.	515

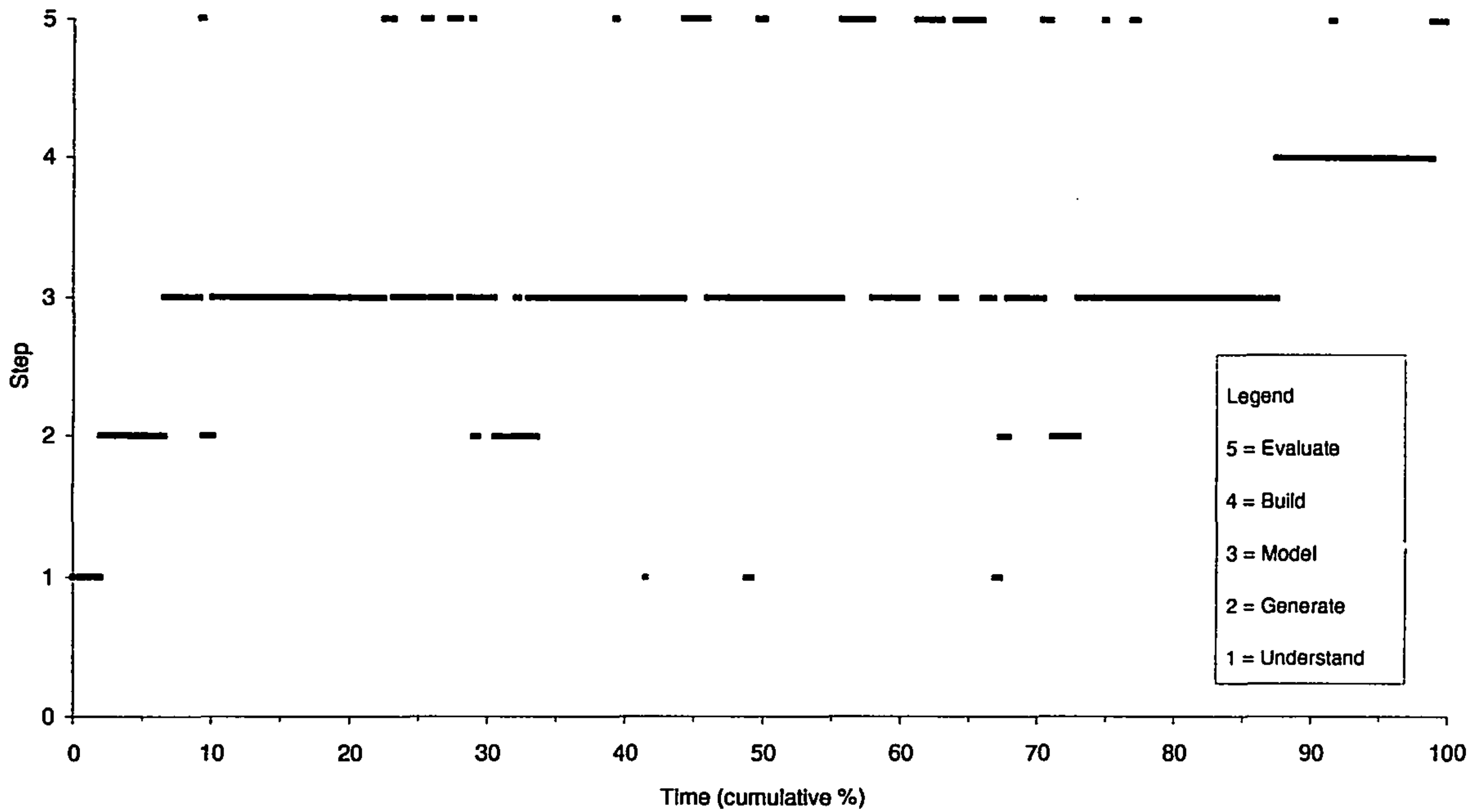


Figure 22. Sequence of steps employed by dyad 5

Subjects engaged in discussion, made drawings and manipulated materials as they explored ideas (Generate).

Satisfied with a new solution they began to make a second mock-up (Model). There followed a period during which subjects consistently used a model-evaluate-model sequence to arrive at a second mock-up. This came to an end when they were unable to make the tower stand for the required 30 seconds (Evaluate). At this point S10 reread the design brief (Understand) and suggested:

S10	What about something similar	832
	except I'm going to do a spiral	833
	thing and I'm going to do a base.	834

She explained her idea to S9 by cutting off a strip of pink paper and rolling it into a cylinder (Generate). When completed she stood the cylinder (Evaluate), after which both subjects sat quietly until S9 began to discuss a third solution (Generate). S10 picked up the idea and described a third possible solution (Generate). Subjects then model-evaluate-model a third solution. When this successful solution, taller that either of the previous two, stood for the required 30 seconds both subjects began to make a replica in white paper, that is, the prototype (Build).

The early stages of building a solution show subjects alternately planning and making the prototype (Build). This was followed by a short test (Evaluation), which lead to completion of the prototype and a final evaluation when subjects stood the tower, timed the required 30 seconds and measured the height of the tower (550 millimetres). Neither subject recorded on paper the height of the tower.

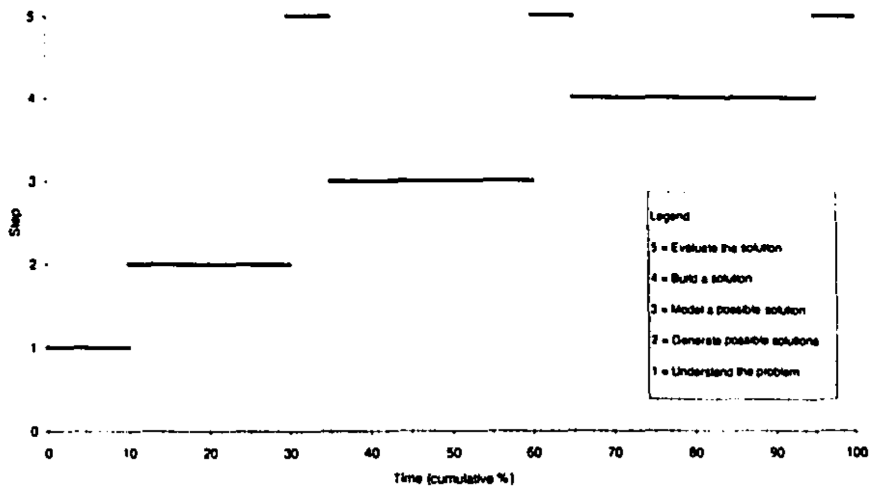
Question 4. How do the strategies used by students differ from those in theoretical models of the design process?

The technological task provided to subjects in this study required them to engage in five steps of the design process: understanding the problem, generating possible solutions, modelling a possible solution, building a solution, and evaluating a solution. Understanding the problem involved, in this case, subjects reading a design brief provided by the researcher. Generating possible solutions was anticipated to involve subjects in discussion and sketching several alternative solutions. Modelling a possible solution would require subjects to give three-dimensional reality to one of the solutions they had sketched. Building a solution would require subjects to replicate a successful model. Evaluating required making judgments about the success of a solution using performance criteria contained in the design brief. In the theoretical model evaluating is seen to occur on three separate occasions: after several possible solutions have been generated, upon completion of a model, and finally when a prototype has been built.

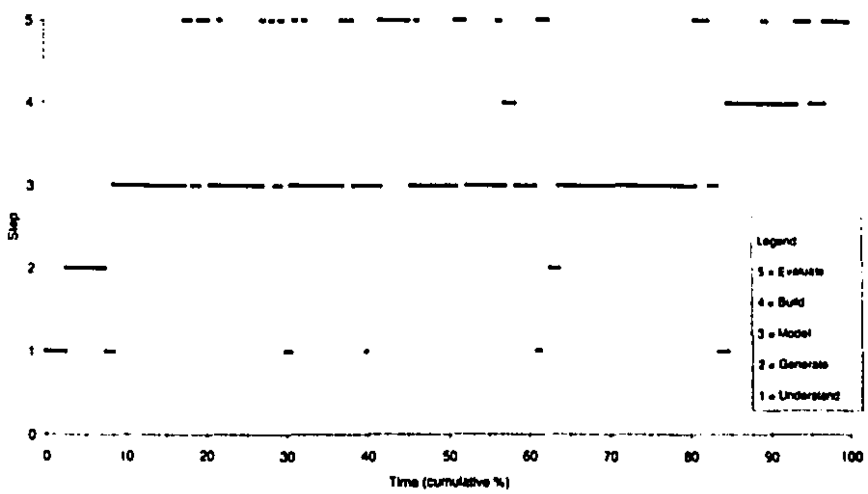
An analysis of the way in which design strategies used by subjects in this study differ from those in a theoretical model of the design process is made possible by visually comparing a map of the subjects' strategy with a map of the theoretical model.

A Comparison Between the Strategy Used by Dyad 1 and the Theoretical Model

As predicted by the theoretical model Dyad 1 first spent time understanding the problem (reading the design brief) before beginning to discuss and sketch possible solutions (Figure 23). Clearly subjects did not spend as much time as



Map of the five-step theoretical design process used in this study



Sequence of steps employed by dyad 1

<u>Figure 23</u>. A comparison between the strategy used by Dyad 1 and the theoretical model

predicted sketching (generating possible solutions). Subjects did not develop detailed sketches of several possible solutions. In fact they produced only one partially completed sketch before beginning to model.

Modelling remains a dominant strand throughout most of their problem-solving session. Several references are made to the design brief during this time.

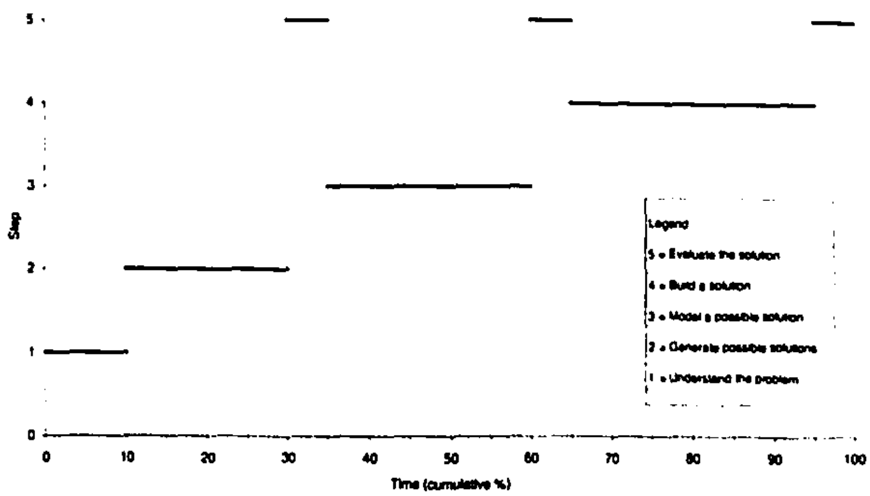
Once a satisfactory model had been completed subjects spent a shorter than predicted amount of time building a solution. Once complete the success of the solution was judged against performance criteria contained in the design brief.

A striking difference between the strategy used by Dyad 1 and the theoretical model is the amount of time subjects spent evaluating their solution. Clearly subjects were constantly evaluating while both modelling their first solution and building a prototype. However, they did not evaluate the second mock-up until it was completed. And unlike the prediction of the theoretical model, which suggests that evaluation occurs only at the end of modelling, subjects in Dyad 1 were evaluating both throughout the entire time they were modelling and building a prototype.

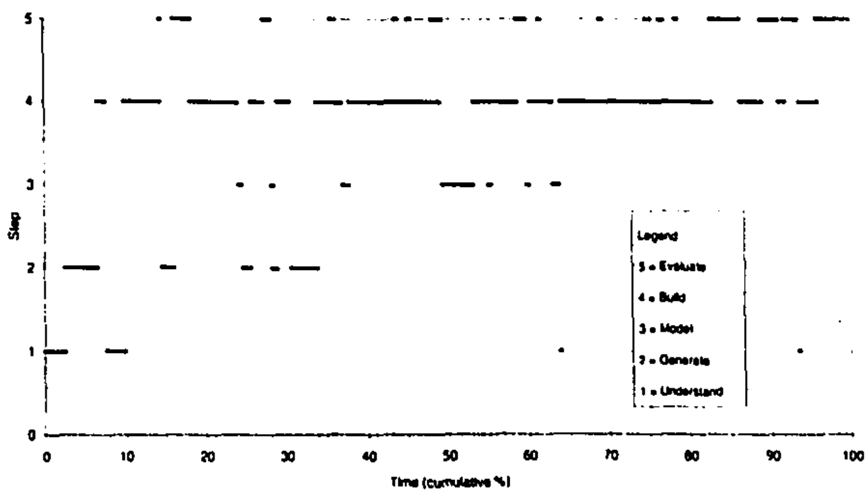
A Comparison Between the Strategy Used by Dyad 2 and the Theoretical Model

Figure 24 highlights the idiosyncratic strategy used by Dyad 2 to which reference has been made several times in this chapter. Having read the design brief subjects sketched one possible solution. They then moved immediately (either deliberately or inadvertently) to building a prototype, without any attempt to model a solution. They omitted completely the modelling step.

The early stages of building a prototype were punctuated by several very



Map of the five-step theoretical design process used in this study



Sequence of steps employed by dyad 2

Figure 24. A comparison between the strategy used by Dyad 2 and the theoretical model

brief periods of sketching, but these involved additions to the original sketch, rather than completely new ideas. In other words, there was several modest attempts to refine the same idea.

As can be seen subjects did engage in some model building, but this was not an integral part of their work. Occasionally one or other subject would attempt to explain a refinement by almost casually picking up a piece of material and bending it or shaping it in an attempt to enhance the current solution.

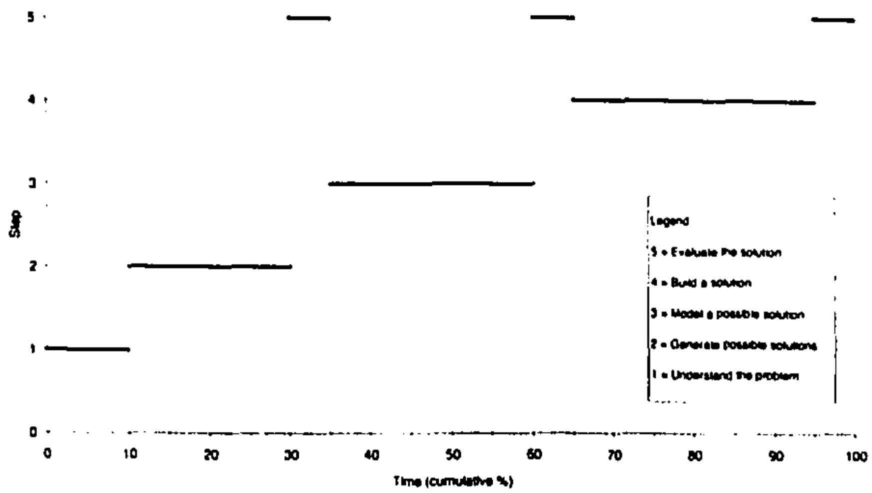
What is evident however is subjects' frequent evaluation of the prototype as it was being developed. Evaluation occurred throughout the entire process of building a prototype and a clear pattern of build-evaluate-build can be seen.

A Comparison Between the Strategy Used by Dyad 3 and the Theoretical Model

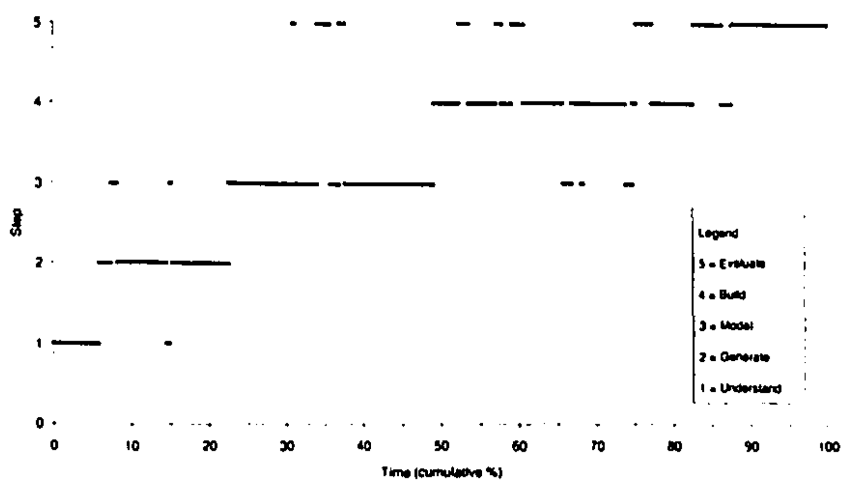
The strategy used by Dyad 3 most closely approximates the theoretical model (Figure 25). Subjects began by reading the design brief before sketching and discussing one possible solution. Note that the amount of time spent discussing and sketching possible solutions is significantly shorter than in the theoretical model. No attempt was made to sketch several possible solutions.

A relatively short time was spent modelling, perhaps because only one simple idea was explored. Subjects evaluated their model on three occasions, but not once it was complete.

Having successfully completed a model subjects built a prototype, evaluating several times during its construction.



Map of the five-step theoretical design process used in this study



Sequence of steps employed by dyad 3

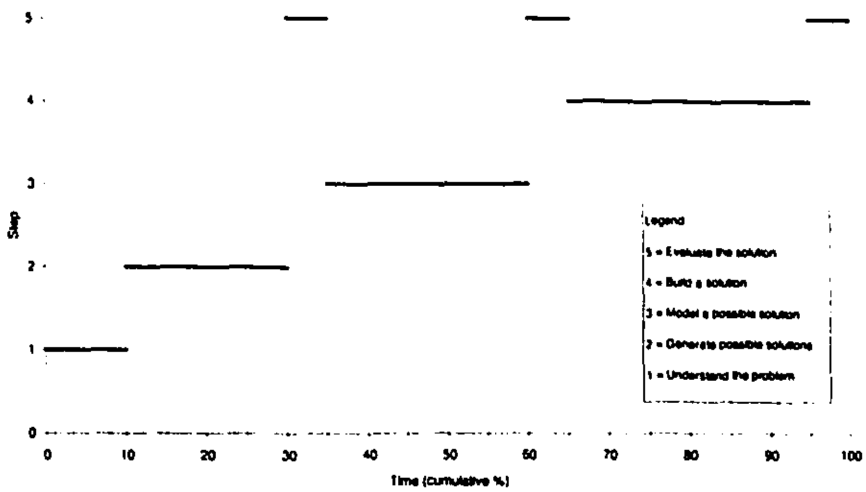
Figure 25. A comparison between the strategy used by Dyad 3 and the theoretical model

A Comparison Between the Strategy Used by Dyad 4 and the Theoretical Model

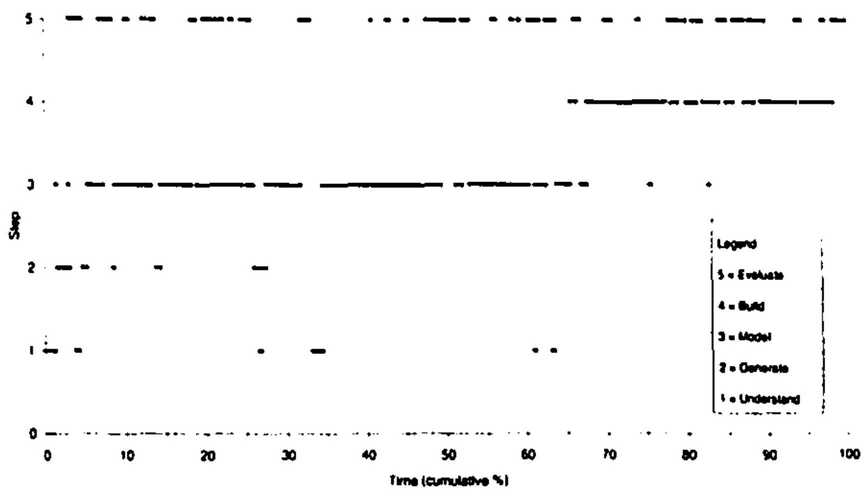
The strategy used by subjects in Dyad 4 is clearly more complex than suggested by the theoretical model (Figure 26). As described earlier in the chapter subjects modelled four different ideas before returning to improve model three. When this was complete they realized that they had not abided by one of the constraints (using a maximum of 100 millimetres of tape) and so decided to replicate the improved version of model three using only the permitted materials.

Although there are five separate instances of subjects discussing and sketching a possible solution each is very short. Much more time is spent exploring possible solutions by modelling in three-dimensional materials. It can be seen that each period of modelling was preceded by a very short period of generating ideas by discussion and sketching. Subjects in Dyad 4 also made five references back to the design brief while modelling.

Notable again is the frequency with which subjects evaluate their progress toward a solution. Subjects were alternately modelling and evaluating or building and evaluating throughout the entire time.



Map of the five-step theoretical design process used in this study



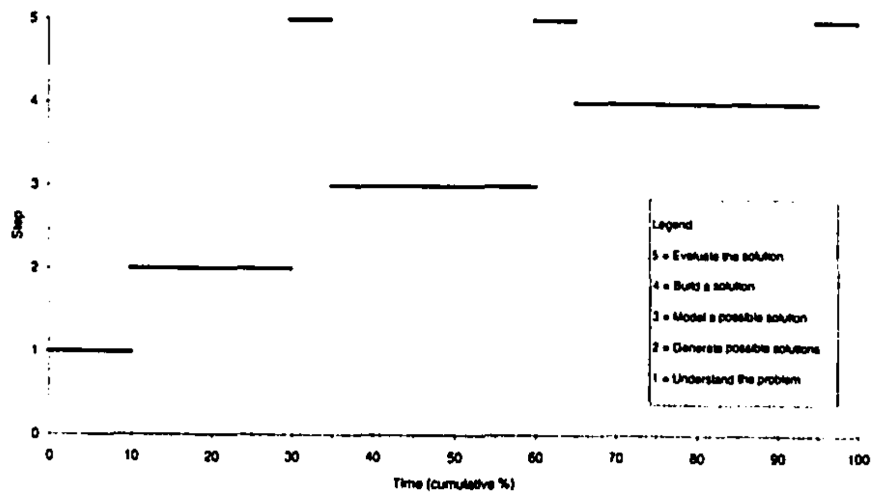
Sequence of steps employed by dyad 4

Figure 26. A comparison between the strategy used by Dyad 4 and the theoretical model

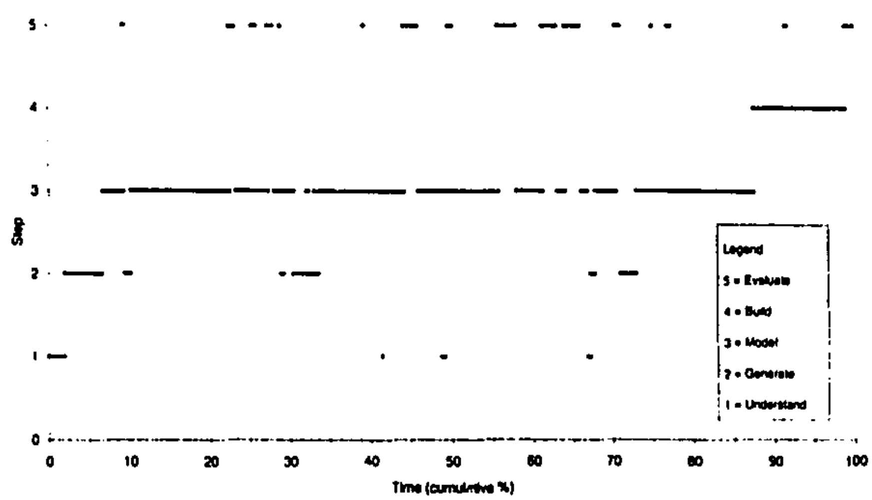
A Comparison Between the Strategy Used by Dyad 5 and the Theoretical Model

A very clear pattern is evident to describe the strategy used by Dyad 5 (Figure 27). After reading the design brief subjects spent time discussing and sketching a first possible solution. This was then modelled and evaluated. Note that very little evaluation occurred while modelling was in progress. There then followed a second period of discussion, sketching and modelling. Evaluation occurred throughout this second period of modelling. A third short period of discussion and sketching was followed by modelling another solution. Some evaluation occurred during the early stages of this third period of modelling but very little in the latter stages.

Having agreed that the third solution was the best, subjects built a prototype. It is notable that subjects in Dyad 5 spent much less time building a prototype than subjects in previous dyads. Very little evaluation occurred while building the prototype, but a short period of evaluation occurred at the end.



Map of the five-step theoretical design process used in this study



Sequence of steps employed by dyad 5

Figure 27. A comparison between the strategy used by Dyad 5 and the theoretical model

Summary

This chapter has reported the data collected from the observation of ten Grade 7 students, grouped into five single-sex dyads, as they developed a solution to a technological problem.

An analysis of the steps of the theoretical models of the design process which are present in students' strategies (Question 1) showed that subjects spent an average of 4.76% of their time understanding the problem, 9.36% generating possible solutions, 37.62% modelling a possible solution, 27.73% building a solution, and 20.53% evaluating solutions. Both modelling and evaluation consumed significantly more time than predicted by theoretical models, while generating possible solutions (by discussion and sketching) significantly less time than predicted.

Question 2 required the production and description of a map for each dyad to describe their design process. Each map plotted the time devoted to, and sequence of, 24 empirically derived codes which together describe a design process. Analysis showed that subjects employed a design process more complex, fragmented and iterative than suggested by theoretical models.

Question 3 focussed on the sequence in which subjects employed steps of the design process. To accomplish this analysis new maps were generated which showed the sequence of steps (rather than the sequence of individual codes) employed by each dyad. These new maps made evident the frequency with which subjects evaluate both models and prototypes. Subjects were found to frequently adopt a model-test-refine-model iteration during the modelling step and a build-test-build iteration during the building of a prototype step.

The differences between strategies used by subjects and that described in theoretical models was the focus of Question 4. These differences were once again made evident by visually comparing the maps for the five dyads with a map of the theoretical model. The most significant differences between the empirical and theoretical maps included (a) the significantly smaller amount of time spent by subjects discussing and sketching solutions, (b) the significantly longer time devoted to modelling, and (c) the frequency and consistency of evaluation.

The final chapter in this study will discuss these results and draw some conclusions about the design process used by the subjects. Some implications for the teaching of technology, and recommendations for further research will be presented.

CHAPTER 5: DISCUSSION

"Design, like science or scholarship, is the product of a distinctive kind of activity and is governed by a distinctive capacity of mind."
(Roberts, P., Archer, B., & Baynes, K. , 1992, p.3)

Overview of the Study

A model of the design process to be used by students to solve a technological problem is included in most textbooks used in technology education. Early versions of these models, derived theoretically rather than empirically, were algorithmic, recommending that a student work steadily and sequentially through a series of steps. Later models contained feedback loops, which linked the evaluation of a final product to the initial identification and description of the problem.

Only quite recently has research begun to produce models of the design process based on empirical data derived from the observation of students as they engaged in designing and making products (Johnsey, 1995a; Kimbell et al., 1991; Roden, 1995). These most recent models reflect the heuristic nature of the act of designing, noting that designing requires a set of skills which may be utilized at various times and in various sequences as the designer works from identifying a problem to producing a solution. This paucity of empirically derived models led to the general research question underlying this study: What design process do students, who have received no prior instruction, use to solve a technological problem?

The design process models described in the technology education literature have provided a significant portion of the theoretical base for this study.

However the study has also drawn on other areas of knowledge and research. In particular, it has applied a general problem-solving model and elements of both multiple-case study and protocol analysis methodologies. The general problem-solving model provided a framework for thinking about the way in which subjects solved a technological problem, while a multiple-case study and protocol analysis methodology provided relevant data.

The design process model used as a theoretical basis for this study contained five steps: understanding the problem, generating possible solutions, modelling a solution, building a solution, and evaluating a solution. Subjects were given a task which, according to the technology education literature, would require them to engage in each of these five steps. Protocols made from both video and audio recordings of subjects' designing were coded using an empirically derived scheme. Codes describing subjects' designing-in-action were identified and a series of maps made evident the design process used by subjects.

The results obtained, and described previously, will be discussed in the four sections of this chapter, using as headings the research questions which guided this study. The significance of the study, both in terms of the theory which underlies technology education and its practice in classrooms, will be addressed. The chapter will end with an acknowledgement of the limitations of the study and recommendations for further research.

Question 1. Which steps contained in theoretical models of the design process are present in student strategies?

This study arose out of the researcher's observation that students, when left to their own devices in an environment rich in three-dimensional materials, frequently resolve a technological problem in unique and creative ways. Further, the steps they follow to achieve a solution do not conform, either in number or sequence, to those described in the technology education literature or school textbooks. Hence the first research question addressed in this study allowed an investigation, in a holistic way, of the design process, that is, the sequence of steps, used by Grade 7 students to solve a technological problem.

According to the literature (described in Chapter 2) subjects could be anticipated to follow a typical sequence of steps in moving from the problem statement to a solution: understanding the problem, generating possible solutions, modelling a possible solution, building a solution, and evaluating the solution.

The next section of this chapter will discuss the results contained in Chapter 4 as they pertain to each of these five steps.

Understanding the Problem

The design brief given to the subjects clearly set out the problem to be solved: Using one sheet of 220 x 280 mm white paper and 100 mm of clear tape, construct the tallest possible tower that will stand for thirty seconds.

If subjects had been asked to think aloud as they read the problem we might expect to find, as Hayes (1989) suggests "that their reading ... reflected a whirlwind of internal activities - imaging, inferencing, decision making, and retrieving of knowledge from memory - activities which are directed toward understanding the problem" (p. 5). Further, in their efforts to increase understanding of the problem we could also reasonably expect to observe subjects reading the problem several times, pausing over any challenging parts. Yet this did not happen. With the exception of Dyad 4, in which S8 read the design brief out loud to her partner, all subjects read silently through the design brief just once before moving to generating possible solutions. When asked if there were any questions about the design brief all subjects except S5, who wanted to know if a microphone stand could be used in the solution, and S2 and S10 who requested confirmation that all the materials on the table were available to them for their problem solving, answered "No". Subjects moved very quickly to solution generation. Subjects did not appreciate the importance of analyzing and focussing on the problem before "jumping straight to design ideas" (Harding, 1995, p. 19). This finding is supported by research on expert/novice problem solving, which has shown that at the beginning of a problem-solving episode experts spend more time attempting to "understand" the problem, whereas novices move more quickly to solution generation (Chi, Glaser, & Farr, 1988; Stewart & Van Kirk, 1990). Yet the designer needs to be sure of exactly what it is they are being asked to do. The fact that Dyad 2 did not model any solutions using the materials provided for that step, but moved immediately to using the materials intended for building a prototype provides evidence of the difficulties which may be encountered when the novice designer does not take the time to carefully read and thoughtfully interpret a design brief. Students in school must be taught and encouraged to spend time thinking about and discussing exactly what is to be achieved.

Generating Possible Solutions

As Cross (1994) has so elegantly stated "the generation of solutions is, of course, the essential, central aspect of designing ... the whole purpose of design is to make a proposal for something new - something which does not yet exist" (p. 105). The UK National Curriculum emphasizes that "children should be taught to 'generate ideas' and this is surely at the heart of design" (Department for Education, 1995, p. 2).

Analysis of the way in which subjects in this study generated possible solutions has made evident four characteristic behaviours: (a) their previous knowledge is drawn on in order to generate solutions; (b) sketching is not a method by which subjects intuitively explore solutions; (c) discussion between subjects plays a major role in the clarification of ideas; and (d) subjects rely heavily on simultaneously discussing a solution while manipulating materials.

According to Hayes (1989) "it is a very rare event for a person to solve a problem without making some use of their own knowledge of ... the world" (p. 51). There is evidence from this study to support the findings of Kimbell, Stables, and Green (1995) that when subjects are generating solutions "previous knowledge is drawn on and developed in new contexts" (p. 34), and "as soon as we begin to perceive the outline of a task, pictures or images of solutions start to appear in our minds" (Kelly, Kimbell, Patterson, Saxton, & Stables, 1987, p. 12). For example, when asked, during a retrospective interview, about their first thoughts and to describe any pictures which entered their heads after reading the design brief one subject replied in the following way:

S9:	I, I thought of the CN Tower	45
	because it's a free-standing structure	46

Her partner's response to the same question was:

S10;	High sky buildings. High-rises.	82

S3 also made reference to the CN Tower.

Not only did subjects make use of previous knowledge gained prior to beginning the task, but there is clear evidence that subjects utilized knowledge gained from successful experiences during the task. For example, Dyad 4 built their second tower by cutting a sheet of paper lengthways, rolling two cylinders and joining them end-to-end to create a tower 21 inches tall. Having recorded the height on paper the following task talk occurs:

S7:	What else?	291
S8:	OK, um we could cut it in three.	293

S8 is suggesting that they could adopt the same idea (cylinders atop one another) but that three will be taller than two.

Without exception design process models contained in the technology education literature include a step during which the student must sketch and evaluate several possible solutions (i.e., design proposals) prior to any attempt at modelling in three-dimensional materials. In other words, not only should students explore and develop early ideas through the medium of sketching, but they should develop a range of possible solutions from which they can subsequently select the most promising. This importance of sketching ideas, of creating "external representations" (Hayes, 1989, p. 5) of a possible solution is a point of agreement in all design process models. The utility of sketching ideas is described by Schön (1987), who points out that while "the act of drawing can be rapid and spontaneous ... the residual traces are stable. The designer can examine them at leisure ... The designer can ... think about what he [sic] is doing; and events that would take a long time in the built world ... can be made to 'happen' immediately in the drawing" (p. 75).

Cross (1994) describes how when professional designers are asked to discuss their abilities, and to explain how they work, they identify "the need to use sketches ... as a way to explore the problem" (p. 17). Cross (1994) quotes the engineering designer Jack Howe, who has said that, when uncertain how to proceed "I draw something. Even if it's 'potty', I draw it. The act of drawing seems to clarify my thoughts" (p. 17). Sketching possible solutions is a critical and necessary step in the generation of design solutions.

Table 4 illustrated how little time subjects in this study devoted to generating possible solutions either by sketching or discussion prior to modelling a possible solution. As will be discussed later in this chapter the preferred strategy used by subjects to develop their ideas was to model in three-dimensional form.

Sketching played an especially small part in the development of a solution (Table 4). Nor was sketching viewed as a necessary first step in the development of a solution. For example S6, having read the design brief, immediately asked "How are we going to construct it?" (lines 109-110). Presumably it was some image in the subject's "mind's eye" which he wanted to model immediately. Equally clear is that, for this subject, there was no recognition of the need to explore and evaluate the merits of several possible solutions, it being singular.

Subjects S3, S4 and S5 did make perfunctory attempts at sketching a solution, but these were quickly discarded in favour of exploring possible solutions by manipulating materials. This lack of importance ascribed to sketching is further supported by the actions of S5 who, after making an incomplete sketch on a sheet of pink paper, immediately began to use the same paper to model and explain an idea to his partner. When asked during the retrospective interview why he not only stopped sketching but used the sheet of paper on which he had sketched to model the idea, he replied:

S5:	Well, I was drawing and then I	230
	thought that um, well this isn't	231
	working very well. Let's see what I	233
	try to figure out what I can do. So	234

um, I started fooling around with the
paper and I completely forgot about
the drawing.

However, the issue may not be that the subjects did not recognize the usefulness of sketching, but that they did not have the skills to either sketch ideas effectively or use sketches to make decisions. The following excerpt from the retrospective interview with Dyad 2 illustrates this point:

R: Alright, [S4], you right there
took pink paper for yourself and gave
one to [S3]. Why did you do that?
S4: Oh, 'cause you said we could only
use white paper so I thought the pink
we could like draw our ideas.
R: Okay, so your initial, your first
thought was that we better draw some
ideas.
S4: Yeah, before we start anything.
R: Alright. [S3] can you think what,
can you remember what your first, what
did you think you had to do first?
What were you planning to do
immediately?
S3: We have to, ah, make the base
first, cause ah, the top part would be
hard like but we had to um, draw it to
get some kind of idea.

But then later:

R: Can you remember [S3], how many
ideas, different ideas you had in your
mind at this particular point?
S3: Ah, I had a couple of ideas but
just drew one.
R: Can you tell me why you decided to
just draw one?
S3: Ah, cause when I drew it, when I
draw too many then it gets confusing.
R: Okay.
S4: Yeah, it's kind of like you have to
pick which one you want and then you
might get confused.

Equally evident is the fact that subjects did not generate a range of possible solutions from which they could choose the one with the most potential for a satisfactory solution. For example, during the retrospective interview the following response was given to the researcher's question "What were your first thoughts after you had read the design brief?"

S3:	I just thought of stuff like how to	117
	make it. I was already thinking	118
	about, like what kind of ideas should	119
	I start with.	120
R:	Umm hum. Can you remember what	122
	some of those ideas were?	123
S3:	Well the first one that popped	125
	into my mind was this one.	126
R:	Okay. The one that you drew.	128
S3:	Yeh.	130
R:	Alright.	132
S3:	And then after I said Okay,	134
	that looks, like, good. I don't think I	135
	have to do anything else to it.	136

In all cases subjects proposed and developed one solution before setting this aside and apparently starting at the beginning, that is, thinking up a next solution. Interestingly, this next solution was frequently a modification and extension of the first.

A small number of empirical studies have provided evidence that this strategy is also true for expert designers (Darke, 1979; Eastman, 1970). Darke (1979) proposed, based on a study of six professional architects, a generator-conjecture-analysis model. Early in the process of designing a simple idea, or primary generator, is used to narrow the range of possible solutions. This primary generator is subsequently used as a basis for further exploration of the problem. Darke goes on to speculate that once an initial concept has been generated it is tested against various constraints and requirements and modified as necessary.

The importance of sketching ideas is not diminished by the evidence that neither expert nor novice designers begin by sketching several possible solutions. The evidence from this study suggests that it is probably unrealistic to expect untutored designers to either sketch or generate several different solutions prior to modelling one of them in three-dimensional form.

The data also suggest that students must be encouraged to become more deliberate in their thinking and to record their ideas by sketching. They must be taught how to think about their ideas carefully and to work them out with greater precision, rather than adopt their first or most obvious idea.

Discussion played a very significant role in subjects' attempts to generate a solution and appeared to provide an informal and supportive way for subjects to develop their ideas. Table 4 showed that subjects spent approximately four times longer discussing solutions than silently sketching them and that the vast majority of their time spent sketching involved simultaneously sketching and discussing a solution. An example of subjects exploring possible solutions via discussion is provided by the following excerpt of the task talk between S9 and S10:

S10:	Okay, then how do you want, how	543
	should we have the tall part?	544
S9:	Would a tree work? Like if we	546
	took like something like this and just	547
	rolled it and then took the other branches	548
	or something.	549
S10:	Yeah, um,um.	551
	What if we made yeah, little rolls	553
	and made it in a teepee style?	554
S9:	Yeah, totem pole like.	556
S10:	Yeah, just like make some rolls	558
	bigger than others. Let's try that.	559
S9:	Okay. I'll cut	561

It appears that students need little encouragement to talk about their ideas. It is important to permit this, for as the Department for Education in the UK suggest "by talking about the quality of their own work and the work of others children learn to evaluate" (Department for Education, n.d., no page). However, it appears students must be taught to use sketches to clarify and show details of their design thinking. This approach is supported by Schön (1987) who wrote "drawing and talking make the designer's thinking accessible" (p. 80).

Simultaneously discussing and manipulating materials was also a preferred strategy of subjects. Often the verbal descriptions of a solution by a subject to their partner was accompanied by the bending or folding of a sheet of paper. The data suggests that this is an important strategy for students as they attempt to clarify, explore and communicate their ideas. In other words, it appears that it is not appropriate to require students to only think about and/or sketch solutions. It appears they must be given the opportunity, indeed encouraged, to explore their ideas using not just the two-dimensional modelling techniques (sketching) but also three-dimensional modelling.

Modelling a Possible Solution

Modelling in all its forms (two-dimensional, three-dimensional, mathematical, and computer) is an essential feature of designing and making (Murray, 1992; Smith, 1993). Modelling not only makes ideas more accessible to oneself and others, but facilitates testing and evaluation, which can lead to refinement and the development of further ideas.

The theoretical model of the design process predicts that modelling in three-dimensional form will occur after students have generated and recorded in graphical form several possible solutions. Like sketching, modelling is intended to externalize ideas but in three-dimensional form. As Liddament (1993) has described "[three-dimensional] models are intended to take information in some less developed form (e.g., notes, sketches, or ideas in the head) in order to develop or refine this information in various ways, thus rendering it more accessible or intelligible" (p. 92).

Subjects in this study used three-dimensional modelling in a number of ways: to transform a two-dimensional model, that is, a sketch, into a three-dimensional form; to externalize a cognitive model; to fuel ideas for further cognitive modelling, which then needed to be tried out in concrete form; and to evaluate a solution.

Table 5 showed that subjects spent, on average, less than one percent of their time planning prior to making a model. However, it would be unwise to assume, based on these data, that planning was not occurring. While very little overt evidence, either in the form of task talk or actions, provided data for this activity, it seems plausible to suggest that subjects were planning what to do next as they were modelling.

As described earlier subjects in this study spent very little time externalizing their cognitive modelling by making sketches. Figures 13-17 show that subjects moved very quickly to modelling in three-dimensional form. In other words, subjects did not use modelling to further develop some "less-developed form", but rather to "originate [and] develop ... their ideas' (Evans & Wormald, 1993, p. 97). Modelling replaced sketching as a way for subjects to generate ideas. Table 2 showed that, on average, far more time was spent modelling than on any other step in the design process. This evidence suggests that it may be unreasonable to expect modelling to occur only after one or more design ideas have been generated and sketched. It appears that simultaneously generating ideas and modelling was an important strategy for subjects. Modelling was clearly an important aid to subjects' thinking about a solution. Concrete modelling appeared to fuel ideas for further cognitive modelling, which were then in turn tried out in concrete form.

Little time was spent planning. Yet planning, "the process of thinking before acting " (Hayes, 1989, p. 58) is critical if designing is to be a predictive rather than a trial-and-error process. As Johnsey (1995a) has also observed subjects were anxious to begin making even before they had clarified their ideas about what to make and how best this might be achieved. This led to a considerable amount of designing by trial-and-error. But as Harrison (1992) has pointed out "part of technological capability is being able to design in a predictive way, rather than by trial-and-error" (p. 35).

Perhaps, as Barlex (1995) has commented, "it [is] far more valuable to learn by making mistakes than to follow a formula and learn less" (p. 7). The evidence from this study also suggests that subjects did not have the skills or knowledge to enable predictive designing to take place. As Harrison (1992) suggests. "modelling in three-dimensions in a range of materials [may be] an important way to establish the skills which would, in the future, allow predictive designing" (p. 35). The richness of this experience for the student was described by Johnsey (1995a) when he wrote "this early interaction with materials means the student is simultaneously researching the problem, generating solutions, learning tools skills and qualities of materials" (p. 19).

The maps shown in Figures 13-17 also make evident the large percentage of their time subjects spent modelling. This included time spent manipulating materials to explore one element of a possible solution, making or refining a mock-up, and checking available resources and materials..

Clearly the "hands-on" approach was the preferred strategy of these untutored designers as they explored ideas and developed a solution. Kimbell et al., (1995) also found that "the driving force behind the activity [of designing] is the making, with planning and evaluating happening throughout but in a short-term, responsive way" (p. 32).

The data also suggest that seeing an idea translated into a three-dimensional model stimulates additional idea generation. For example, S9 and S10 are sitting silently looking at a previous model consisting of a sheet of paper rolled into a cylinder. The following task talk then occurs:

S9:	Do you know how those card things,	854
	you know how they build big castles out	855
	of cards?	856

S10 holds a piece of paper on top of the cylinder from a previous model and says:

S10:	What if we did something like cut	863
	that like that and then put a base	864
	around it, put the base to it and	865
	added little pieces of paper at the	866
	top. Watch, I'll show you.	867
S9:	You need a base around the bottom	869
	if you're going to put all that weight	870
	at the top.	871

S9 takes a strip of paper, folds it into a large circle and fixes it to the base of the tall, thin cylinder.

When Dyad 4 have successfully completed a tower made by cutting a sheet of paper into two equal parts, rolling and taping them into cylinders, and joining them end-to-end, S8 says "Okay, um, we could cut it [a sheet of paper] in three" (lines 293-294).

Modelling not only allowed subjects to develop new ideas, but also allowed them to refine ideas. For example, Dyad 1 had rolled and taped two identical cylinders and were about to make it stand. However, before this could occur S1 interrupted and said, "Let's cut the bottom out to make sure it stands" (lines 305-306). S2 then proceeded to cut and bend four tabs at the bottom edge of the tower in order to form a base.

It appears therefore that modelling in three dimensions was a very rich experience for subjects. While it played a minimal role in translating two-dimensional models (sketches) into three-dimensional form, it was crucial for the realization of subjects' cognitive modelling, and for encouraging design modifications to be an ongoing part of the process. Many other steps in the design process may have been occurring simultaneously with modelling. Subjects were perhaps planning what to do next as they were completing a modelling task. They may have been evaluating as modelling continued. They may have been generating ideas as a result of a successful or unsuccessful test. "Modelling [allows] subjects to simultaneously explore, develop and communicate aspects of their design proposals" (Department for Education, 1995, p. 4).

This evidence supports Murray's (1992) view that "modelling activity is a tight iterative relationship between imaging and modelling as designing and making proceeds" (p. 38).

Building a Solution

For the purposes of this study building a solution involved subjects in the construction of a "final model" (Evans, 1992) of a design proposal. In essence subjects were expected to replicate their most successful (that is, the tallest tower that would stand for at least 30 seconds) working model in a more finished form (a prototype). In a school setting a final model is often the end product of a design and make activity (Royal College of Art, 1995). As Harrison (1992) has noted "most making in schools is actually modelling" (p. 33).

Table 2 showed that the time spent by individual dyads building a solution varied considerably. Dyads 1 and 5 spent the least time (11.22% and 11.26% respectively). This is probably explained by the fact that both these dyads took great care to produce a carefully crafted model which met the performance criteria contained in the design brief. Hence building a solution involved, for these subjects, little more than accurately replicating the model.

Dyads 3 and 4 however used a quite different strategy. They spent 35.44 and 22.87 percent respectively of their time building a solution. While some of this time was spent simply replicating a successful model, in both cases the majority of the time spent on this step involved modifying and improving the design of the prototype. Discussion will return to this point later in this section.

The idiosyncratic strategy adopted by Dyad 2 has been noted previously, and accounts for the fact that 31.44 percent of their time spent building a solution was devoted to making modifications (MODPR), for their prototype served as both a model (an exploration of design ideas which involved ongoing generation and development of ideas) and as a final model, that is, a prototype. Dyad 2 moved directly from generating possible solutions to building a solution. No attempt was made to model a variety of solutions using the materials provided specifically for this. This explains why 57.88 percent of their time was spent building a solution, that is, prototyping.

When asked, during the retrospective interview, why they had not used the modelling materials S4 replied "I just thought, let's ... just go for it" (lines 351-352). His partner's response to the same question was "I saw ... just one piece of white paper ... we'll just use that" (lines 360-361). Clearly the opportunity to explore a variety of solutions was not seen as an important part of the process by these subjects. Nor did they read the design brief sufficiently carefully to understand that particular materials had been provided for modelling.

Table 6 showed considerable variability in the time devoted by subjects to modifying and improving the prototype. Several examples from the protocols will be used to illustrate the point that for the most part these modifications involved technical rather than design changes. For example, Dyad 1 spent very little time (1.74%) making modifications while building a solution. However, these modifications involved technical changes in response to an identified performance problem, rather than fundamental changes to the design of the solution.The following excerpt of task talk, which occurred after their prototype failed to stand for more than a few seconds, illustrates the point:

S2:	It fell, it fell.	863
	Too much of an angle.	865
S1:	We have to untape this and put it	867
	there.	868

S2 identified a performance problem ("Too much of an angle"), which prompted S1 to immediately suggest a technical improvement ("We have to untape this [lower part of the cylinder] and put it [the tape] there [lower on the cylinder]").

Dyad 5 made no design or technical modifications while building a solution. This testifies to both the depth of design thinking which went into the modelling step and to the care with which they crafted a model. For these subjects building a solution involved simply the technical task of replicating a successful model.

Table 6 showed that while some of the time spent by Dyads 3 and 4 building a solution was devoted to replicating a model (MPR = 12.75% and 5.29% respectively), much more time was spent modifying and improving the prototype

(MODPR = 17.32% and 17.25% respectively). This suggests that Dyads 3 and 4 had not fully worked out a satisfactory solution prior to building the prototype. Furthermore, this data suggests that these subjects did not view the two activities of modelling and building a solution as discrete steps, but that designing, that is, generating and incorporating new ideas, continued until a satisfactory solution had been achieved.

Further examination of the transcripts shows that very few fundamental design changes were made during the construction of a prototype. Rather, modifications involved simple technical changes: rerolling and taping a cylinder; repositioning a piece of tape; trimming with scissors the bottom edge of a tower to make it flat. For example, after an unsuccessful attempt to stand their tower subjects in Dyad 4 engaged in the following task talk:

S7:	Not again.	1184
S8:	This isn't straight.	1186
	(referring to the bottom edge)	
S7:	... the bottom, have to tape the	1188
	bottom, right?	1189

Clearly this is an example of the identification of a simple technical problem (the bottom edge of the tower has not been cut flat) and its solution.

Subjects in Dyad 3 provide a similar example. When, during an attempt to stand their cylindrical tower for the requisite 30 seconds, S5 sees that one part of the cylinder is unravelling, the following task talk occured:

S5:	I don't think that's going to stay	342
	very well. Just gotta reroll it. make	343
	sure that stays on.	344
S6:	Take off the tape.	346
S5:	The tape's off.	348

Then a little later:

S5:	It looks unbalanced.	352
S6:	It's this part now.	354

(Pointing to unravelled lower cylinder)

There was no attempt to make design modifications, but rather subjects were dealing with purely construction details; tape that would not stick, causing a cylinder to unravel.

Occasionally there is a tight, iterative relationship between identifying a problem, making minor technical changes, generating new design ideas, and incorporating and testing those new ideas. For example, Dyad 4 made a number of unsuccessful attempts to stand their tower. It appears that the bottom edge is not flat. S8 suddenly exclaims "Ah, if we make it square it will stay" (lines 1294-1295). She then creased the bottom portion of the cylinder so that it formed a square. Unfortunately this also was unsuccessful, and so subjects returned to trimming the bottom edge in an attempt to make it flat. When this was again unsuccessful S8 returned to the design modification and said "We need crisp corners" (line 1314). She then recreased the square, but again was unable to make the tower stand. She then suggested a second design modification:

S8:	Maybe if we put a flat thing on	1321
	the bottom?	1322

but this idea was rejected by S7 and subjects returned to making minor modifications, for example, retaping joints and trimming the bottom edge.

Evaluating

Evaluating when designing and making in technology education is not confined solely to making judgments about an end product (Royal College of Art, 1995). Prior to designing a product the designer must evaluate the needs of the potential consumer. As ideas are generated each needs to be evaluated in order to make decisions about which should be developed further. The designer needs to constantly evaluate progress as designing and making continues. And lastly, but by no means least in an educational context, student designers need to be taught how to evaluate their learning.

In this study evaluating was used as an umbrella term to include four types of activity: (a) making decisions while subjects discussed an idea for a possible solution (EGEN) or discussed a sketch of a possible solution (EDRAW), (b) testing one element of a mock-up (TMU) or prototype (TPR), (c) evaluating a mock-up or prototype in terms of the performance criteria contained in the design brief (EMU and EPR), and (d) recording in written form the height of the mock-up or prototype (RRMU and RRPR).

The rapidity with which subjects moved to developing and refining ideas using three-dimensional materials was illustrated and discussed earlier (Figures 13-17). These also showed that, in general terms, subjects were repeatedly and constantly evaluating their solutions from the first moment that making began. Table 7 showed that subjects spent a little over one-fifth of their time-on-task evaluating in one form or another.

It appears that models of the design process (e.g., Schools Council, 1974) which include evaluating as a summative activity intended to make judgments about an end product do not reflect the strategies of untutored designers. The data provided by this study suggest that evaluating is a recurring activity, starting during the first moments a student reads a problem statement and continuing until a solution has been submitted.

Table 7 showed that little time was spent evaluating ideas as they were discussed or once they had been drawn. This is not entirely surprising, given the relatively small amount of time devoted to these activities (3.20% and 0.85%

respectively). The one exception to this lack of evaluating during discussion or while sketching occured when subjects S3 and S4 had made a base for a tower and were deciding how many strips of paper were required to make a column. The task talk was as follows:

S4:	Okay, we have to, ah, know how much	237
	we're going to cut the piece. Put one	238
	in each corner or like one, two, three	239
	four?	240
S3:	We'll put one in each corner.	242
S4:	So make, make two more.	244

This suggests that the teaching of designing must focus on this element, for as the Department for Education in the UK suggest in a recently published brochure for parents "by talking about ... their own work ... children learn to evaluate" (Department for Education, n.d., no page). There is a need to focus on not only, as suggested earlier in this chapter, teaching students how to externalize their ideas in the form of sketches, but for the need to critically evaluate sketched ideas before moving to the next step, and the method for doing this. Students must be taught to evaluate their design ideas from the first moment these ideas begin to emerge.

Testing during modelling often lead to the identification of a design problem and suggested refinements. For example, Dyad 5 spent several minutes constructing a tower which had failed to stand because its vertical supports were insufficiently rigid to support its own mass:

S10:	Need more weight on this part.	475
	(points to vertical column)	
S9:	Yeah.	477
S10:	Even if we put ... why is it tipping	479
	over?	480
	Why is it tipping over?	482
S9:	It's too much weight ...	484
S10:	On one side.	486
S9:	If we put a base around here now.	488

The data also suggest that evaluating led to the acquisition of knowledge which subsequently informed the design of a future solution. For example, Dyad 5 abandoned their first solution when it would not stand because, although the lower section was rigid, the top section was too heavy. After a few moments spent cleaning the work space and organizing the tools and materials, the following task talk occurred:

S10:	Okay: Definitely need a base.	525
S9:	Yeah.	527
S10	A bigger base. More sturdy.	529
	Like that, much more base.	531
S9:	Yeah.	533

Evaluating a product in terms of performance criteria contained in the design brief is obviously an important, ongoing concern for the designer. Hence it is important that the designer not only understand the performance criteria but that they remain at the forefront of thinking. Evidence from this study confirms that even after a single reading the performance criteria contained in the design brief were constantly in the minds of the subjects. For example, when S2 stands the first model made by Dyad 1, he immediately reacts by saying "It seems too small" (line 427). This suggests that he was aware that one of the performance criteria was to build the tallest tower. Later, this same subject says to his partner, as modelling continued, "We're going for the height, right" (line 525). S3 asks his partner "Let's see how high" (Dyad 2, line 672). When their model stands S8 asked "Okay, so how tall is this?" (Dyad 4, line 157). Later, S7 remarked "Has to be taller" (Dyad 4, line 271). Subjects were aware that the tower had to stand for 30 seconds. S4 asked the rhetorical question "This has to stand for 30 seconds, eh?" (Dyad 2, lines 719-720). S6 told his partner "You have to wait for 30 seconds" (Dyad 3, line 464). Subjects' awareness of the criteria for the tower to be free-standing was also evident. For example, S7 asked her partner "Will it stand? (Dyad 4, line 141).

Evaluating either a model or prototype involved measuring the height of the tallest tower, and timing the 30 seconds it was required to stand. When S2 rolled a sheet of pink paper into a cone, taped the seam, and then stood it on the table he declared "It's tall, it's free-standing, and it won't fall. It's not as tall, but it's tall, it's freestanding and it won't fall (Dyad 1, lines 577-580). His response was in part in frustration, for prior to this episode he and his partner had been singularly unsuccessful in making a previous mock-up stand for even a few seconds. His use of the term tall suggests relief at the fact that the model remained vertical. A little later, after his partner has measured the height of the cone, both subjects express their lack of satisfaction with the solution:

S2:	Not the most beautiful looking	653
	thing.	654
S1:	It's not that tall either.	656

Table 7 showed that of the five dyads only Dyad 4 recorded the results of testing a model. Not only were they the only Dyad to do this, but they were consistent in the practice. They recorded the height of all four successful mock-ups. Only three of the five dyads recorded on paper the height of the completed prototype. These data suggest that students must be made aware of the importance of maintaining written records of performance results as designing proceeds.

Question 2. What design process do Grade 7 students, working in single-sex dyads, use to solve a technological problem?

As described in Chapter 4 and shown in Figure 11 the literature predicts that subjects in this study would utilize an essentially algorithmic, linear design process to accomplish the designated task, that is, build the tallest possible tower from one sheet of paper. Subjects would be anticipated to spend a short time reading the design brief, following which they would discuss and sketch a range of solutions. From these they would model one which they judged to be the most likely to be successful, that is, be the tallest and stand for the requisite 30 seconds. A refined model, evaluated to be successful, would be replicated as a prototype, which in turn would be evaluated against the performance criteria contained in the design brief.

Clearly this simple linear progression does not describe the design process used by subjects in this study. Even the strategy used by Dyad 3, which most closely approximates the theoretical model, differs from it in significant ways. Their process is far more fragmented than the theoretical model suggests it would be. Subjects are frequently toing-and-froing between steps. This fragmentation of the process and the toing-and-froing between steps is most evident in the later stages of the process when subjects in Dyads 1, 4 and 5 are modelling a solution or building a prototype. In these cases there is evident a clear, repeating pattern of model-test-refine-model (when modelling a possible solution) or build-test-build (when building a prototype). There is even a period during the building of a prototype when subjects in Dyad 3 return to modelling one element of the solution. Clearly any form of linear process does not reflect what subjects in this study did when designing.

Discussion was clearly an important part of the process for subjects, usually occurring simultaneously with another activity. For example, subjects often simultaneously sketched an idea and explained it to their partner. This was an attempt to clarify ideas, possibly for both the speaker and the partner. As Schön (1987) has observed "drawing and talking are parallel ways of designing and together make up ... the language of designing" (p. 45).

In a recent study Kimball, Stables, and Green (1995) also found that subjects spent a considerable amount of time talking through a problem and its solution: "Thus ongoing discussion appears to be a major means of planning their way through the task" (p. 32). Similarly subjects frequently discussed an idea while simultaneously manipulating materials, that is, modelled an idea in three dimensions while describing it in words.

A further radical difference between the theoretical model of the design process and the actual process used by subjects is the frequency with which they evaluate their ongoing designing. It seems reasonable to expect that while subjects are generating several possible solutions through discussion and sketching (as theoretical models suggest they must before beginning to model) they would be constantly evaluating. The literature does not make this explicit, but clearly subjects in this study were doing just that. All five dyads evaluate their progress from the moment they begin to explore possible solutions to the moment they declare that they are finished. This supports the suggestion of Harding (1995) when she writes that "design, like any other intellectual activity, gives shape to ideas through ... expression in cycles of continuous refinement" (p. 19).

Question 3. In what sequence do students employ steps of the design process?

This study derived, in part, from the researcher's observation that High School technology education students do not use the sequence of steps described in textbook models of the design process to solve a technological problem. Data presented earlier in this study have shown that subjects used two strategies which are at odds with those described in textbook models. The first of these is that rather than generating and sketching several possible solutions prior to modelling one which is evaluated as the best solution, subjects develop solutions serially. That is, they discuss, model, and evaluate a solution which may or may not be abandoned. If the first solution is abandoned, then a second solution is developed. In this way Dyad 1 developed two solutions, Dyad 4 developed five solutions, and Dyad 5 developed three solutions.

The large percentage of time-on-task devoted by subjects to both modelling and evaluating has been discussed earlier. Similarly, the various forms of evaluating have been described. Data showed that these two steps occur in a repeating cycle which may be described as a model-test-refine-test iteration. This iteration represents a second significant difference between textbook models of the design process and strategies used by subjects in this study.

The Serial Development of Solutions

Chapter 2 described how, in textbook models of the design process, students are expected to sketch several possible solutions prior to selecting and modelling the one which they judge to offer the most promise as an effective solution. Data presented in this study have shown that this was not the intuitive strategy of subjects. They were more likely to develop solutions serially. When, for example, Dyad 5 had completed a first model which failed to stand for the requisite 30 seconds, S10 suddenly suggested abandoning the solution, and the following task talk occurred:

S10:	Let's do something different.	496
S9:	Okay. It did work a little bit.	498
S10:	It worked there for a few seconds	500
	there.	501
S9:	Okay.	503

New one. 505
S10: Use a fresh sheet. 507

Subjects then discussed a second solution, (essentially a tripod made from rolled cylinders) which they modelled. When they were unable to make this second model stand for 30 seconds it also was abandoned and subjects began a discussion of a third possible solution. This is but one example of a strategy which may be described as the serial development of solutions. In other words, an idea is generated, developed as a model, evaluated, and then abandoned. A second idea, sometimes although not always informed by the experience and knowledge gained from the first model, is similarly developed. Figure 28 shows this iteration diagrammatically.

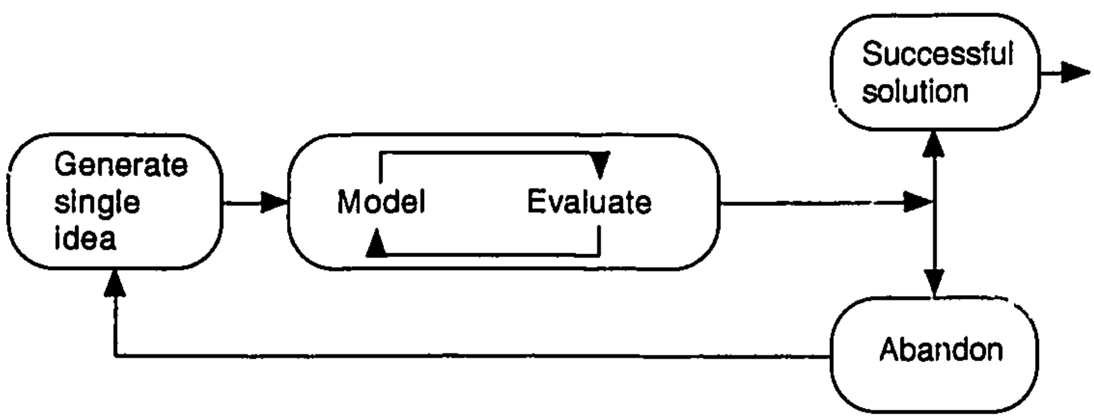


Figure 28. The serial development of solutions

Note that model and evaluate have been shown as one step, for as discussed earlier in this chapter, these two activities form a repeating iteration as subjects constantly cycle between them. However, as will be described in the next section of this chapter, this cycle is not as simple as portrayed here.

<u>The Model-Test-Refine-Test Iteration</u>

The previous section included <u>model-evaluate</u> as a subset of a larger iteration. In fact, evidence suggests that this two-part subset is more complex than this. The following example, taken from the transcript for Dyad 4, will illustrate the point.

Subjects S7 and S8 had previously rolled and taped one sheet of paper into a single cylinder 280 millimetres tall. S8 began to discuss (GEN) how a single sheet of paper could be cut into two strips, each of which could be rolled into a cylinder before combining the two cylinders:

S8:	You could cut it and then roll	174
	half of it and roll the other half and	175
	stick it together to make it tall.	176

Her partner agreed:

S7	Oh yeah, try it.	178

S8 cut the paper into two equal pieces, each 140 x 220 millimetres (Model). Each subject then rolled and taped one piece into a cylinder (Model).

S7:	How's this?	182
S8:	Roll it this way.	184
S7:	Tape the side so it will stay.	186
	Here.	187
	We'll tape the bottom together.	189

S8 then took the cylinder made by S7 and joined the two together (Model).

S8:	Okay, yours is strong so we can	191
	stick it, I'll just ...	192
S7:	I hope it stands. This won't, no,	194
	this won't stand up.	195
	(Attempts to stand one section - Test)	
S8:	... put a little tape.	197
S7:	Okay, will it stand?	199

S7 attempted unsuccessfully to stand the tower (Evaluate). S8 identified what she thought was the problem:

S8: I just got to make it even on the bottom.

S8 used scissors to trim the bottom edge of the tower (Refine). S7 made a second unsuccessful attempt to stand the tower (Evaluate). S8 again used the scissors to trim the bottom edge (Refine). The next attempt to stand the tower was successful (Evaluate) and so S7 measured its height (Evaluate). This example provides clear evidence of a model-test-refine-test iteration. Figure 29 shows the sequence graphically.

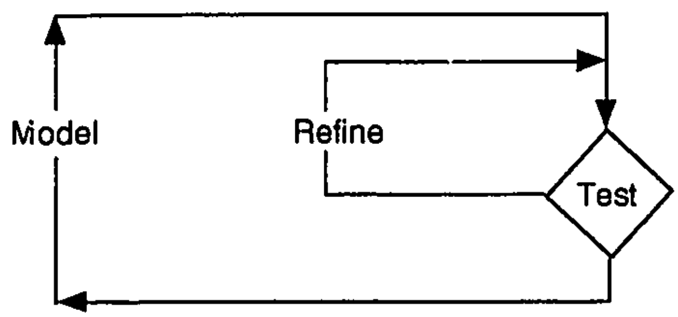


Figure 29. The model-test-refine-test iteration

What the data also make evident is that subjects frequently repeated the test-refine-test part of the loop before returning to modelling. This sequence of activities may be an important aspect of the behaviour of untutored designers, for while modelling subjects appeared to be increasing their understanding of the problem, generating additional solutions, refining ideas, exploring the properties of materials, and practising tool skills. Schön (1987) captured the richness of this experience when he wrote "designing is a creative activity. A designer's reflective conversation with the materials of a situation can yield new discoveries, meanings, and inventions" (p. 161).

Question 4. How do the strategies used by students differ from those in theoretical models of the design process?

The differences between the design strategies used by subjects in this study and theoretical models described in textbooks was made evident by visually comparing the maps of the subjects' strategies with a map of the theoretical model (Figures 23-27). Four very significant differences were identified and illustrated using both examples of task talk and design episodes contained in transcriptions of subjects' design activity.

First, students' strategies are more complex than suggested by any of the linear models. Figures 23-27 showed that subjects frequently do not work in a linear way through the steps identified in textbook models: understand the problem, generate possible solutions, model a solution, build a solution, and evaluate a solution. Understanding the problem appears to emerge from an exploration of solutions. Subjects did not sketch and evaluate several solutions prior to modelling but generated and modelled serially. Modelling itself was shown to be a complex activity, more accurately described by a model-test-refine-test iteration. This iteration itself appears to act as a source of inspiration for new solutions. Similarly, building a prototype involved an iteration, a constant toing-and-froing between building, testing, and refining. Evaluation occurred not as a summative activity after generating and modelling and building, but as an integral and ongoing activity.

Second, subjects generated solutions serially rather than generating several at the outset. Subjects in this study did not begin designing by sketching several possible solutions. Data have shown that no subjects attempted to sketch more than one solution at the outset, and that such sketching as did occur was perfunctory.

Third, it appears that the preferred strategy for developing ideas is modelling in three-dimensional form. Subjects moved to modelling much sooner than predicted by textbook models. The evidence suggests that untutored designers are anxious to begin modelling, even before a solution has been fully worked out.

Modelling served several purposes: externalizing ideas, providing a method of testing and refining and evaluating ideas, and stimulating new ideas. Modelling appears to be an essential stimulus to the ongoing development of ideas. The interaction with materials appeared to stimulate other design skills. It is important, therefore, for teachers to recognize when modelling is aiding their other designing skills.

Fourth, Figures 23-27 illustrated quite clearly how evaluating was an integral and ongoing activity when subjects in this study were designing. Evaluating occurred consistently from the earliest moments of designing. As Archer and Roberts (1992) have written:

> All design activity involves continual appraisal and reappraisal of the meritoriousness of existing realities and alternative propositions being handled.
>
> There is also the transitive form of the same activity which is wholly or largely concerned with the appreciation of states of affairs and with choosing and deciding, rather than with the creation of things and systems. (p. 4)

Specific Contributions of this Study

The introduction to this study described how, because of its relatively recent introduction into the school curriculum, technology education has but a limited corpus of empirically derived research findings to support the development of curricula. This study adds to that corpus by developing and implementing a methodology for investigating the strategies used by untutored designers. Both the methodology used and the findings of this study have implications for the theory and practice of technology education. In particular, they have implications for the way in which designing is taught to students. These implications will be discussed under the subheadings of theoretical significance and implications for teaching.

Theoretical Significance

The review of literature on models of the design process to be used in technology education suggested a discontinuity between the theoretical models, that is, models derived by thinking about what designers ought to do, and empirical models, that is, models which describe what designers actually do. This discontinuity was further supported by the classroom observations of the researcher; that Grade 7 students, left to their own devices, do not design in the way prescribed by textbooks. Hence the research questions which drove this study were designed to lead to an understanding of how untutored designers solve a technological problem. Therefore one particular contribution of this study has been to examine in detail the actual practice of a small sample of untutored designers.

Since the internal mental processing of a problem solver is inaccessible to direct observation the researcher, in order to obtain information about an individual's problem-solving processes, must find a method of requiring the subject to reveal the steps being followed so that an observable sequence of processes will be available for analysis. In this study the naturally occurring conversation between subjects in a dyad was recorded. The resulting protocol was then available for analysis. While protocol analysis is being used increasingly for investigating various aspects of technology education (Elmer, 1996; Johnsey, 1995a; Roden, 1995) this study represents one of the earliest in which the subjects' actions and associated task talk were recorded and analyzed. A second contribution of this study has been therefore to substantiate protocol analysis as an appropriate methodology for the investigation of untutored designers' behaviour.

The set of assumptions about the general structure of problem-solving processes postulated by both Ericsson and Simon (1984) and Hayes (1989), plus design process models in the technology education literature provided a theoretical framework for the development of a scheme consisting of "start codes" to describe the actions of subjects in this study. This coding scheme was then refined using the inductive approach advocated by Glaser and Strauss (1967) and Strauss (1987). Codes "grounded", that is, derived from, the data were used to develop a more comprehensive, detailed and descriptive coding scheme. Thus this study provides the first detailed analysis of the actions of untutored designers using a coding scheme grounded in the qualitative analysis literature.

Implications for Teaching

This study derived from the researcher's first-hand experience with attempts to teach designing and making using theoretical models of the design process contained in relevant textbooks. The results of this study have suggested that subjects' naturalistic design strategies do not match these models. Hence these results contain implications for teaching children how to design and make.

The most significant result to emerge from this study was the critical role of modelling in three-dimensional materials as an aid to subjects' thinking. Modelling was used to support a range of activities: increasing understanding of the problem, stimulating the generation of solutions, seeing what a design would look like, testing, and continuously incorporating modifications and improvements into a solution. This is perhaps no surprise, for as Hayes (1989) has written "much of our knowledge of solution strategies is acquired rather unsystematically through our daily experience in solving problems" (p. 52). The bulk of students' untutored technological problem-solving skill will have been acquired in the material world: building sand castles, using commercial construction kits, constructing with found materials, and so on.

This empirical explanation for a subject's preference for modelling ideas in three-dimensional materials is further supported by Piagetian learning theory. Piaget (1964) postulated that the thinking of senior elementary school students (Grade 7 subjects in this study) is at the concrete operations stage. The student thinks in terms of concrete, existing objects and is not yet able to use abstractions. Therefore, the requirement that untutored technology education students sketch several possible solutions, that is, work in an abstract form, before modelling in three-dimensional materials is not supported by either empirical observation, learning theory, or the results of this study. Rather, it appears that teachers should encourage modelling with three-dimensional materials early in the process. It appears important to provide students, early in the process, an opportunity to explore, develop and communicate aspects of their design proposals by modelling their ideas in three-dimensional form.

However, this may pose something of a difficulty, for, as Hayes (1989) has described, there are significant disadvantages to moving too quickly to a "task environment ... the real-world context in which the task is to be performed" (p. 59), rather than operating in "a planning environment ... a symbolic representation that can substitute for the real world when we are thinking about the problem" (p. 59). For novice designers there are disadvantages to working with three-dimensional materials, which will require the use of materials and tools, prior to planning and exploring ideas, which will require the use of a sketch pad and drafting board.

Hayes (1989) identifies three reasons why it is important for problem solvers to plan, that is, translate from task environment to the planning environment. First, in many task environments moves once made cannot be unmade. For example, in this study, when subjects in Dyad 2 began to explore a solution using the materials intended for prototype building, they unwittingly committed themselves to an error-free strategy, for once consumed the materials could not be reconstituted. Moves in the planning environment are nearly always reversible. A line on a sketch can be erased and redrawn.

Second, it is less costly, in terms of time and resources, to make moves in the planning environment than to make the corresponding move in the task environment. It would have been less "costly", in terms of time and materials and effort, for subjects to have sketched their solutions prior to making a model. Optimization of the best solution becomes simpler in the planning environment, for the rapidity with which sketches can be made facilitates the comparison of solutions en route to a "best" solution.

Third, working in the planning environment permits a flexibility not available in the task environment. Hayes provides the example of an architect who, in planning a hotel, will begin with crude bubble diagrams "to indicate the general positions of major unit" (p. 61), which lead to "drawings ... [which are] more detailed and specific until the final drawings become ... blueprints for construction" (p. 62). This type of abstract planning cannot occur in the designers' task environment. They cannot build abstract, that is, conceptually incomplete, products.

These observations from Hayes and the results of this study suggest that students must be taught to work efficiently in a planning environment before moving to the task environment. Yet previous research has shown how students with no prior technology education do not have the skills to represent in two-dimensional form an object which will eventually be made using three-dimensional materials (Constable, 1994a). There is often a mismatch between students' imaginative abilities and their representational skills (Anning, 1993).

Young children can make drawings after they have worked with materials, but cannot predict what a final design will look like (Anning, 1993; Constable, 1994a, 1994b). Novice designers must be taught not only the skill of drawing, but also to use drawings as a way to record and explore, to think through, in an abstract way, their design ideas.

At the same time, given the importance to subjects in this study of modelling in three-dimensional materials, teachers of technology education must think about the relationship between two-dimensional and three-dimensional modelling and the difficulties that students appear to experience in making the transition between the two.

The results of this study also suggest there is reason to doubt the efficacy of requiring students to follow any form of linear or sequential design process model. The study has shown that untutored designers do engage in many of the sub-processes of theoretical models, but they do not prioritize or sequence these sub-processes as suggested by the models. Clearly for subjects in this study the design process was not a rigid framework to be applied strictly. It appears, as Wise (1990) has suggested, that "the design process is a set of reminders of what might be involved" (p. 27).

The results suggest that a simple draw it-make it sequence described in most models published to date may not be an appropriate way to develop design capability. Kimbell, Stables, and Green (1995) have suggested that "there is no overall, single form of design process" (p. 32). The results of this study support this finding. This, in turn, suggests that there may be no one way to teach designing to students.

The complexity of the process used by subjects in this study suggests a need for teachers to focus explicitly on the teaching of design process skills that will assist students' problem solving, but not impose a strict sequence in which those skills are applied. As Barlex (1995) has observed, it is "important to ... retain the spirit of experimentation in the design process ... [and] to encourage pupils to find their own methods and frameworks for thinking about problems" (p. 7).

Yet at the same time, as Kimbell (1990) has described, students must be provided with a superstructure to designing. They must be able to think and work strategically, so that when time runs out at the end of a project they are where they want to be. Hence designing combines dynamic thinking within the project with the metacognitive task of being able to stand back and have an overview of the whole that will lead to a satisfactory conclusion. As Schön (1987) has pointed out designing is a holistic skill which may be broken into component parts for the purposes of teaching. But at the same time the student must "grasp it as a whole in order to grasp it at all" (p. 158). The student "cannot learn it in a molecular way ...for the pieces ... interact with one another and derive their meaning ... from the whole process in which they are embedded" (p. 158).

This study has also made evident the dominant place of evaluating as subjects were designing. It appears that teachers need to focus the attention of students on this activity and stress its importance. Ongoing evaluation is likely to increase the quality of both the end product and the ability of the student to design effectively. A recognition of the model-test-refine-test iteration so dominant in the strategies used by subjects should, as Johnsey (1995a) has also found, encourage teachers to take a broader view of the nature and role of evaluating when students are designing.

Limitations of the Study

Chapter 3 described the limitations inherent in the methodology adopted for this study, and the steps taken to minimize their effect. For example, the difficulties arising from the use of dyads and the need to ensure that subjects worked cooperatively rather than singly was minimized by the researcher's timely reminders to "Work as a team".

A limitation of the study arises out of the size of the sample. The small sample (five dyads) would appear to be a barrier to external validity. However, while the total sample is small, each case study was very detailed. The recording of subjects' actions and task talk, and a retrospective interview produced a significant amount of rich data. And further, as Yin (1989) points out "[any] analogy to samples and universes is incorrect when dealing with case studies ... because survey research relies on statistical generalization, whereas case studies rely on analytical generalization" (p. 43). In other words, case studies are generalizable to theoretical propositions and not to populations.

The case study does not represent a sample and the researcher's goal is to expand and generalize theories and not to enumerate frequencies, that is, statistical generalizations. The results of this study, while not representative or generalizable, may be seen as characteristic of a small group of untutored designers.

Recommendations for Further Research

This study has suggested that there exist significant differences between design processes described in the technology education literature and the actual processes used by untutored designers. The following are suggestions for further research which may lead to yet increased understanding of this newly emerging part of the curriculum.

Modelling in three-dimensional materials has been seen to play a large, central role in the solving of a technological problem. Further research might seek to compare the quality of design solutions from two groups; one of which is required to draw and then replicate those drawings in three-dimensional materials, and the other is permitted to investigate solutions by manipulating three-dimensional materials from the first instant. If, as suggested by this study, more effective use can be made of modelling in the development of students' technological capability, an attempt must be made to analyse the use of modelling. Which form of modelling best allows students to externalize ideas? Which form of modelling encourages the exploration of the greatest number of ideas? Which form of modelling is least inhibiting to the flow of ideas?

Subjects in this study were provided with a particular design brief which included performance criteria. As a result, the strategies they used to solve the problem may have been a function of that particular problem and the way in which it was presented. Would subjects employ a similar strategy if given a different problem? Does the nature of the problem determine or influence the strategy? If the starting point were a context from which subjects were required to identify a specific task would the strategy change?

The finite number and quantity of tools and materials provided to subjects may in themselves suggest particular solutions. Further study could provide subjects with a much broader range of tools and materials, either to solve the same problem presented in this study or, as suggested earlier, to solve a problem defined by the subjects.

Grade 7 students with no prior technology education provided the sample for this study. Future research could track the development of novice designers' skills as they receive formal instruction in designing and making. Of particular interest would be the mapping of the development of technological capability from junior kindergarten to high school.

The influence of tacit knowledge, both on the particular task and on problem solving in general, would be a productive area for research. A deeper understanding of how students make use of tacit knowledge when designing is needed. Once this has been achieved, teachers will be significantly better placed to plan technology education curricula.

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APPENDIX A - RESEARCH APPLICATION TO SCHOOL BOARD

Date: 27 11 92
D/ M/ Y/

BOARD OF EDUCATION
Research and Assessment Department

RESEARCH APPLICATION

All sections of the Application Form must be completed and typed in full before the proposal will be considered. An abstract of the study, letter of consent, and all instruments used in the study need to be appended to this form. Please submit EIGHT copies of the application form. PROPOSALS MUST BE SUBMITTED EIGHT WORKING DAYS BEFORE THE COMMITTEE MEETING. Proposals submitted after APRIL 1st will not be considered for this school year.

1. General information

(a) Title of Research Proposal: Grade 7 students' conceptions of the design process within a technological context.

(b) Name: Malcolm Welch Degrees: B.A.(Hons); M.Ed.

Address: University of Toronto Phone: (416) 978 2992

Faculty of Education, 371 Bloor St. W., Toronto, Ont. M5S 2R7

(c) Sponsoring Institution or Agency: ____________

McGill University Phone: (514) 398 6952

(d) Please check one:

___ Undergraduate Thesis
___ Masters Thesis
_X_ Doctoral Thesis
___ Ministry-funded project
___ Institutionally funded project
___ Other ____________

2. Overview and Relevance of Research Study

(a) Brief Description of the Problem and Research Goals:

The purpose of this study is to investigate the problem solving strategies of students as they attempt to find a solution to a technological problem. The study derives initially from the observation of the researcher that students appear to have an intuitive sense of how to problem solve in a technological context. The steps they follow to achieve a solution, however, often do not conform, either in number or in sequence, to those described in textbooks. Some of the elements of the "correct" process, such as sketching and investigation, are frequently omitted by students. Others, such as testing and evaluation, are evident but are not used in the sequence described. Hence, it would appear that the formal teaching of problem solving frequently conflicts with the intuitive strategies students bring to the technology classroom.

(b) List the Specific Hypotheses Tested or Research Questions asked in this Study:

Research questions:

1.0 What concept of technological problem solving do Grade 7 students hold prior to instruction?

1.1 Which elements of the design process exist in student strategies?

1.2 Which elements of the design process are missing from student strategies?

1.3 In what sequence do students employ elements of the design process?

2.0 In what ways do the strategies of boys and girls differ?

(c) Potential Application of this Project to Education:

If teaching and learning is to be "student centred" rather than "teacher centred", it is important to understand students' approach to technological problem solving. Such an understanding will make it possible to build upon, rather than ignore, the students' prior knowledge.

(d) Direct Benefit to Students and/or Staff (e.g., through feedback, workshops, materials, etc.):

Current Ministry of Education initiatives in the restructuring of education in Ontario include that Design and Technology become a compulsory component of the curriculum for all students at all grade levels. Since problem solving lies at the heart of technology, then it becomes essential that teachers of technology have a thorough understanding of the process. In-service workshops, based on the results of this research, will be provided for teachers.

(e) How will confidentiality/anonymity be maintained?

The identity of the subjects will be protected by assigning code names to each of them. These code names will be used in all reporting of the results of the study.

(f) How will debriefing and feedback to the subjects be accomplished?

Within five days of the problem solving episode, each pair of students will be interviewed as they watch and listen to the video of their session.

3. Description of Research Methodology

Please attach a one-page abstract which summarizes the research problem, hypotheses, design, methods, and relevance. In addition, please include one copy of the entire proposal.

(a) Study Design (be as specific as possible):

Four dyads will be presented (on four separate occasions) with a problem statement from which they are to develop a technological solution. The problem requires the use of soft materials and simple tools (scissors, ruler, pencil, tape). Each dyad will be audio and videotaped while solving the problem. Subjects will be encouraged to talk normally while problem solving. At a later time (within five days) each dyad will listen to and watch the video of their problem solving while the researcher conducts an interview. During the interview the screen and the students' voices will be recorded (on video) to ensure that the researcher can document the segment of the video being referred to by the students. Analysis of both sets of audio and video tapes, along with the interview protocols, will be used to answer the research questions.

(b) Facilities Required (e.g., special arrangements, facilities, or circumstances; please note that the Research and Assessment Department will not provide assistance in terms of research design, coding, postage, personal delivery of materials, etc.):

The research will require the use of a well-lit room with two large flat tables, one for the subjects to work on and the second for the researcher to place tape recording equipment. All of the equipment (both audio and video recording and the tools and materials for the subjects) will be provided by the researcher.

(c) School characteristics required (e.g., location, size, special characteristics)

The school must have a Grade 7 intake at the general or advanced level. Location is not crucial, although a school south of Highway 401 would be the most convenient.

(d) Data collection (sample):

Subject — Time Required

Students: Grade 7 No. 8 Individual ____ Group 2 hrs

Students will be arranged into four single-sex dyads. Each dyad will require a one-hour time period to complete the experimental activity. This will be followed, within a period of five days, by a second session of one hour during which the students will be debriefed.

Teachers: No. None Individual ____ Group ____

Other persons: None No. ____ Individual ____ Group ____

Number of schools: One

(e) Procedure (describe method of obtaining consent and attach copy of letter of consent; describe sampling procedures, and data gathering process):

Each subject in the study and their parents/guardian will be provided with a copy of the "Letter of consent". This letter is in two parts. Part 1 describes the purpose of the research, the tasks to be performed by the subjects, the right of the subject to withdraw at any time, and the name of all the researchers and institutions involved in the study. Part 2 requires the signature of both the parent/guardian and the subject.

The dyads will be selected in the following way. Having identified a group of students willing to participate, their classroom teacher will be asked to identify pairs of students who work well together or are friends. Data will be gathered by (a) audio and video recording the problem solving sessions, and (b) audio and video recording a retrospective interview with each of the dyads as they watch the video of their problem solving session.

(f) Instruments (list all measures to be used and attach copies):

Students will be provided with an instruction sheet describing the technological problem to be solved (copy attached).

4. Projected Time Frame For Study

(a) Data collection: January 4th - February 26, 1993.

(b) Expected Dates For Submission of Interim Report and Completed Report to The ____ Board of Education's External Research Committee:

Interim Report: August 31, 1993.

Final Report: April, 1994.

(c) Plans For Publication:

It is anticipated that, as is normal practice, the results of this doctoral research will be published in learned journals and presented at conferences. However, at all times the anonymity of the subjects and the participating school board will be respected.

5. Endorsement of Research Study

(a) Signature of Principal Investigator: ____________________
Date: ____________________

(b) Complete if Student Thesis or Research Project:

This is to certify that the above described research proposal has been vetted for its academic soundness. We have given consideration to ethical, legal, and moral questions arising from the proposal. Enclose copy of formal letter from review committee.

Dr. John B. Gradwell

Sponsoring Professor (Please type name and sign)

Date: ____________________________

ABSTRACT

The purpose of this study is to investigate the problem solving strategies of students as they attempt to find a solution to a technological problem. The study derives initially from the observation of the researcher that students appear to have an intuitive sense of how to problem solve in a technological context. The steps they follow to achieve a solution, however, do not conform, either in number or in sequence, to those described in textbooks. Some of the elements of the "correct" process, such as sketching and investigation, are omitted by students. Others, such as testing and evaluation, are evident but are not used in the sequence as described. Hence, the formal teaching of problem solving frequently conflicts with the intuitive strategies the students bring to the technology classroom.

RESEARCH QUESTIONS

1.0 What concept of technological problem solving do Grade 7 students hold prior to instruction?

- 1.1 Which elements of the design process exist in student strategies?
- 1.2 Which elements of the design process are missing from student strategies?
- 1.3 In what sequence do students employ elements of the design process?

2.0 In what ways do the strategies of boys and girls differ?

METHODOLOGY

Grade 7 students will serve as the source of primary data for this study. Four single-sex dyads will be presented with a problem statement and required to develop a technological solution. Each problem solving session will be audio and video recorded by the researcher. Subjects will be encouraged to talk normally during the session. At a later time (within five days) each dyad will watch the video of their problem solving while the researcher conducts a semi-structured interview. During the interview both the screen and the students' will be video recorded to ensure that the researcher can document the segment of the video referred to by the students. A protocol analysis of transcriptions of both the problem solving sessions and post-activity interviews will follow. These data collection procedures will make it possible to triangulate (a) transcripts of the verbal interactions of the dyads, (b) the researcher's notes based on direct observation of the students and later analysis of the video recordings, and (c) the transcripts of the retrospective interviews with each of the dyads.

APPENDIX B - LETTER TO PARENTS AND CONSENT FORM

1993 03 01

Dear Parent/Guardian:

Your son/daughter ________________ is one of a group of Grade 7 students selected as a potential subject for a research study, conducted as part of my doctoral studies at McGill University, Montreal. The study is entitled "Grade 7 students' conceptions of the design process within a technological context".

The aim of this letter is twofold. First, it will describe the purpose and methodology of the research study. Second, it will request that both you and your son/daughter agree, in writing, to participate in the study. Should you or your son/daughter decide not to participate, no further action is required, and I thank you for taking the time to read this material.

The purpose of the study is to investigate and better understand the thought processes of Grade 7 students as they attempt to find a solution to a technological problem. The study derives initially from the observation that students appear to have an intuitive sense of how to problem solve in a technological context. However, the sequence of steps they follow to achieve a solution is often different from that described in much of the technology education literature. Hence the formal teaching of problem solving frequently conflicts with the intuitive strategies students bring to the technology classroom.

The proposed methodology of the study requires that pairs of subjects be presented with a problem statement from which they are to develop a technological solution. The subjects will be asked to talk naturally as they complete the task. Each problem solving session will be both observed and audio/video recorded by the researcher. Sessions will be followed by a semi-structured interview while watching the video. Each session will require one hour of time.

The problem requires the use of soft materials and simple tools (scissors, ruler, pencil, tape, etc.). No student will be required to use tools, materials, or equipment that is dangerous or beyond the existing knowledge of the student.

Agreement on the part of you and your son/daughter to become a part of the study in no way obligates you or your son/daughter to remain a part of the study. Your son/ daughter, or you on their behalf, may choose to withdraw from the study at any time. Further, participation or non-participation will in no way affect any school mark or report your child may receive.

The results of the study will be published as a doctoral dissertation. It is anticipated that parts of the study will be published in professional journals and reported at conferences. At no time will the actual identity of the subjects be disclosed. Subjects will be given code numbers and these only will be used in publications.

Should further information be required before either you or your son/daughter can make a decision about participation, please feel free to telephone me at the University of Toronto, Faculty of Education, (416) 978 2992.

Yours sincerely,

Malcolm Welch
Lecturer, Technological Studies

LETTER OF CONSENT

Grade 7 students' conceptions of the design process within a technological context

I agree to participate in a programme of research conducted through the Faculty of Education at McGill University.

The purpose of the study has been explained to my satisfaction.

I understand that subjects' names will be coded to maintain confidentially.

I understand that, upon request, I may have a full description of the results of the study after its completion.

I give my consent to have the session audio- and videotaped.

I understand that the data from this study may be published.

I understand that I am free to withdraw from this study at any time without negative consequences.

I HAVE READ AND UNDERSTOOD THIS CONSENT FORM AND I AGREE TO ALLOW MY SON/DAUGHTER TO PARTICIPATE IN THE STUDY.

Student's name (PLEASE PRINT): ______________________

Signature of parent/guardian: ______________________

Date: __________ Telephone number: ______________

I HAVE READ AND UNDERSTOOD THIS CONSENT FORM AND I AGREE TO PARTICIPATE IN THE STUDY.

Signature of student: ______________________

Date: ______________

Telephone number: ______________

APPENDIX C - LETTER OF ACCEPTANCE INTO THE STUDY

1993 03 25

Dear Mr. and Mrs. [ ]:

Thank you for agreeing to allow [Name] to participate in the research study "Grade 7 students' conceptions of the design process within a technological context".

The purpose of this letter is to inform you of the dates and times when [Name] will be involved.

[Name]'s first session, during which she will work with another student to solve a technological problem, is scheduled for Monday, April 19, at 11:00 - 12:00 in the seminar room adjacent to the library. The second session, during which time I will interview [Name] and her partner, is scheduled for Thursday, April 22, at 11:00 - 12:00, again in the seminar room.

Should any of these dates and times be inconvenient or impossible as a result of other commitments, please telephone me as soon as possible so that I can reschedule sessions.

Once again, thank you for your interest and support of this research. In due course I shall write to you again to report on the progress of the study.

Yours sincerely,

Malcolm Welch
Lecturer
Technological Education
Telephone: (416) 978 2992

APPENDIX D - LETTER OF THANKS TO NON-SELECTED VOLUNTEERS

1993 03 25

Dear Mr. and Mrs. [Name]:

Thank you for agreeing to allow [Name] to participate in the research study "Grade 7 students' conceptions of the design process within a technological context". The response from parents was very encouraging. It is gratifying to know that so many parents are interested in educational research.

Having obtained the names of students willing to participate, each was assigned a code number. Ten of these were then randomly selected to participate in the first stage of data collection. Unfortunately [Name] was not among those selected. However, there is a possibility that a second group of students will be required. In this case [Name] will again be numbered, along with all those students not selected in the first round, and a random selection made. At this time I will write to you and provide the dates and times when [Name] will be involved.

Once again, thank you for your interest and support of this research.

Yours sincerely,

Malcolm Welch
Lecturer
Technological Education
(416) 978 2992

APPENDIX E - THE DESIGN BRIEF

PAPER TOWER

Problem:

Using ONE sheet of 220 x 280 mm white paper and 100 mm of clear tape, construct the tallest possible tower.

You will also be given pink paper. This you may use in any way as you develop your solution. However, NONE of the pink paper may be used in the tower you submit as a final product.

Limitations:

There is a time limit of one hour.

The tower must be free standing. It cannot be taped to the floor or anything else.

When you have finished, the tower must stand for 30 seconds before having its height measured.

Materials:

1 sheet white paper 220 x 280 mm
100 mm clear tape
Pink paper
Masking tape
1 pair of scissors
1 metric/imperial ruler
1 compass
Pencils
Erasers

APPENDIX F - EQUIPMENT REQUIREMENTS FOR THE PROBLEM SOLVING AND INTERVIEW SESSIONS

EQUIPMENT

PROBLEM SOLVING SESSION	INTERVIEW
Camcorder	Camcorder
Tripod	Tripod
2 lapel microphones	2 lapel microphones
2 extension cords	2 extension cords
Tape recorder	Tape recorder
2 blank VCR tapes	2 blank VCR tapes
2 blank audio tapes	2 blank audio tapes
Extra batteries	Extra batteries
Box of materials	Note pad
Tape measure	Pens
Note pad	Task instructions (interview)
Pens	Transcript of task talk
Masking tape	TV/VCR (at school)
Copy of design brief	VCR tape (task session)
Task instructions (task)	Interview questions

APPENDIX G - INSTRUCTIONS FOR PROBLEM-SOLVING SESSION

INSTRUCTIONS FOR TOWER BUILDING - SCRIPT

Warm-up

Hello. My name is Malcolm Welch and I work at the University of Toronto, where I teach people how to become teachers of technology.

Before we begin we are going to do a sound and video check.

SWITCH ON TAPE AND VIDEO RECORDERS

I would like you to tell me your names, and then describe something that you have made at home. Perhaps you could tell us a little bit about how you built it, what materials it was made of, and whether or not you were pleased with the result.

SUBJECTS' RESPONSES

In each case the researcher will respond with:

"That is very interesting. Thank you for sharing it with us."

OR

"That sounds like fun. Again, thank you for sharing it with us."

CHECK SOUND AND VIDEO

Task instructions

Now I would like to describe to you what we will be doing today and why you are so important. If you have any questions please feel free to interrupt me.

First, let me explain the reason for selecting a group of students to be involved in this research project. Technology is a very new subject in schools and because of this newness teachers are sometimes not sure of the best way to teach it. What we are going to do today and during the second time that we meet is part of a study that is trying to improve the methods used to teach technology.

Your role is very important, and here's what it will involve. In just a moment I am going to give you a sheet of paper on which is described a problem similar to one that a professional technologist might be asked to solve. On the table in front of you there are a number of materials and tools that you can use to solve the problem.

I would like you to read carefully through the description of the problem. If there is anything in the instructions that you don't understand, please ask me and I will try to explain it to you. The only help that I CANNOT give is help in developing a solution. This I want you to do by working together.

As soon as you feel ready you may begin to develop your solution. Remember, you will be working as a pair. This means that you should try to cooperate in everything that you do. As you are working together to develop a solution, please talk to each other in a natural way.

It is important for you to remember that there is no right or wrong answer. Different people will have different solutions to the same problem. What I am most interested in is HOW you solve the problem. Also I want you to remember that this work will NOT count in any of your school marks.

Finally, as you read in my first letter to you, everything that we do is going to be video recorded so that later when we talk about what you did we can watch the video and it will serve to remind you and me of your actions. The tape recorder is a back-up in case the sound of the video fails or is not clear.

GIVE DESIGN BRIEF TO SUBJECTS

Are there any questions?

Just a remimder. You have one hour in which to work. You may use any of the materials on the table, but only the white paper can be used in the solution that you present at the end.

SUBJECTS DESIGNING - ONE HOUR

<u>Ending</u>

At the end of one hour or when students have finished, whichever comes first.

O.k., lets measure the height of your tower.

SET UP TOWER AND HAVE SUBJECTS MEASURE HEIGHT

<u>Thanks</u>

Well, that's all for today.

When we meet on [give day and time] in this same room, we are going to watch the video and I will ask you a few questions about what you did today.

But before you leave, I'm going to ask a very big favour of you both. Some of your friends are also going to be helping me with this project. To help make the results of this experiment more valid I am going to ask you not to tell anyone (except your parents) about the problem you had to solve today. If you tell your friends they have an opportunity to think about it before they arrive here and therefore its as though they have more than the one hour in which to solve the problem. So, if you can keep the problem a secret until everone has finished you would be helping me with the accuracy of this research.

[Name] and [Name], I want to thank you both for your help and I'll see you on [day].

APPENDIX H - INSTRUCTIONS FOR RETROSPECTIVE INTERVIEW

RETROSPECTIVE INTERVIEW - SCRIPT

Welcome back. First of all let me explain to you what we are going to do today.

You will remember that when we met a couple of days ago you worked your way through a technological problem. Would one of you describe to us the problem.

ONE SUBJECT DESCRIBES THE TOWER PROBLEM

ASK SECOND SUBJECT IF THEY HAVE ANYTHING TO ADD

CHECK SOUND AND VIDEO

Since I last saw you I have watched the tape and I now have some questions about what you did, how you solved the problem and why you did what you did.

So in a moment we are going to watch the tape together. As we watch I'm going to pause the tape and ask you some questions. Generally these questions will ask you what you were doing at that moment. I will ask you to try to remember what you were thinking. If you cannot remember clearly, or what you see on screen doesn't make sense to you, just say "I don't remember" or "I don't know why I did that". I'm going to call upon you by name so I'll say things like, "[name], what were you doing there?" or "[name], what were you thinking there?".

Are there any questions before we begin?

BEGIN PLAYING THE VIDEO TAPE

Allow the subjects to watch the tape without asking any questions until the tape reaches the point when both subjects have finished reading the design brief. Pause the tape and then ask each subject in turn: "What sort of pictures entered into your head as you were reading the design brief?" and "What were your first thoughts after reading the design brief?".

CONTINUE PLAYING VIDEOTAPE

Thank you's

Well, that brings to an end your participation in this research. I want to thank you both very much. My job, once all the interviews have been completed, is to watch the tapes of both the tower-building sessions and the interviews and analyse how you went about solving the problem.

When this is complete, I shall be reporting the results to the School Board, your principal and yourselves.

In the meantime, I am once again going to ask you to not discuss this morning's work with your friends until the entire research project is over. The last interview is on Thursday, April 22nd. After that date you are free to talk about what you have done; and I would encourage you to discuss this with your friends and compare your solutions, problems and questions.

[Name] and [name], again I want to thank you both for your help.

APPENDIX I - CODING SCHEME SHOWING 32 CODES

Theoretical and empirical codes to describe designing

Step	Code (Theoretical &/or empirical)	Definition
Understanding the problem	RBRF	Reading design brief as given to subjects by researcher
	DPERF	Discussing/referring to performance criteria
	DCONS	Discussing/referring to constraints
Generating possible solutions	GEN	Discussing possible solutions
	DRAW	Sketching/drawing possible solutions
Modelling a possible solution	PMU	Planning the making of a mock-up
	MANIP	Manipulating materials to explore one element of a possible solution
	MMU	Making a mock-up
	RMU	Refining a mock-up. making modifications to current solution
	CMMU	Making a copy of a previous mock-up
	ARM	Checking available resources & materials
	ABAN	Abandon current solution, begin new solution
Building a solution	PPR	Planning the production of a prototype
	MPR	Making a prototype
	IPPR	Identifying a problem with a prototype
	MODPR	Modifying and improving the prototype in terms of the original need, i.e., making a design change
Evaluation	EGEN	Evaluating as subjects talk about a possible solution
	EDRAW	Evaluating as subjects talk about a sketch or drawing
	TMU	Testing one element of a mock-up as designing continues
	EMU	Evaluating mock-up in terms of design brief
	TPR	Testing one element of the prototype as making continues
	EPR	Evaluating the prototype in terms of the design brief
	RRMU	Recording results from mock-up
	RRPR	Recording results from prototype

Miscellaneous codes, derived from both the literature and the data

Step	Code	Definition
False start	FS	Statement which indicates an incomplete thought
Off-task talk	OTT	Statement made by a subject which is not directly related to the task at hand
Boundary marker	BM	Um, Ok, Uh, etc
Clarification request	CR	Request from subject to researcher for clarification
Researcher response	RCR	Information provided by researcher in response to a subject's clarification request
Warm up	WU	Warm-up activity to acclimatize subjects to task environment
Researcher introduction	RINTRO	Description by researcher of the research project and general methodology
Comments	RC	Comment or question from the researcher

APPENDIX J - SEQUENCE OF CODES FOR EACH DYAD

Data for graph of Dyad 1

Code	Time on code (secs)	% total time	Elapsed time (secs)	Cumulative %
RBRF	49	2.5	49	2.5
DRAW	36	1.8	85	4.4
GEN/DRAW	15	0.8	100	5.1
GEN	9	0.5	109	5.6
GEN/MANIP	7	0.4	116	5.9
GEN/DRAW	22	1.1	138	7.1
GEN	9	0.5	147	7.5
DCONS	18	0.9	165	8.5
ARM	13	0.7	178	9.1
MMU	5	0.3	183	9.4
ARM	3	0.2	186	9.5
ARM	48	2.5	234	12.0
MMU	87	4.5	321	16.5
RMU	21	1.1	342	17.5
TMU	16	0.8	358	18.4
RMU	20	1.0	378	19.4
TMU	23	1.2	401	20.6
RMU	27	1.4	428	21.9
TMU	2	0.1	430	22.1
MMU	100	5.1	530	27.2
EMU	30	1.5	560	28.7
RMU	15	0.8	575	29.5
EMU	8	0.4	583	29.9
RBRF	7	0.4	590	30.3
DPERF	7	0.4	597	30.6
RMU	11	0.6	608	31.2
EMU	6	0.3	614	31.5
RMU	17	0.9	631	32.4
EMU	5	0.3	636	32.6
RMU	87	4.5	723	37.1
EMU	25	1.3	748	38.4
RMU	29	1.5	777	39.8
DCONS	2	0.1	779	39.9
RMU	36	1.8	815	41.8
EMU	70	3.6	885	45.4
RMU	17	0.9	902	46.3
EMU	4	0.2	906	46.5
RMU	70	3.6	976	50.1

Data for graph of Dyad 1

MANIP	5	0.3	981	50.3
RMU	15	0.8	996	51.1
EMU	25	1.3	1021	52.4
RMU	10	0.5	1031	52.9
MMU	69	3.5	1100	56.4
EMU	8	0.4	1108	56.8
ARM	7	0.4	1115	57.2
MPR	26	1.3	1141	58.5
EPR	49	2.5	1190	61.0
DPERF	10	0.5	1200	61.5
EPR	9	0.5	1209	62.0
EPR	13	0.7	1222	62.7
GEN	22	1.1	1244	63.8
ARM	53	2.7	1297	66.5
MANIP	14	0.7	1311	67.2
MMU	23	1.2	1334	68.4
MANIP	28	1.4	1362	69.8
MMU	71	3.6	1433	73.5
RMU	43	2.2	1476	75.7
MMU	100	5.1	1576	80.8
EMU	32	1.6	1608	82.5
ARM	20	1.0	1628	83.5
DCONS	24	1.2	1652	84.7
MPR	89	4.6	1741	89.3
TPR	10	0.5	1751	89.8
MPR	70	3.6	1821	93.4
EPR	34	1.7	1855	95.1
MODPR	34	1.7	1889	96.9
EPR	29	1.5	1918	98.4
EPR	32	1.6	1950	100.0

Data for graph of Dyad 2

Code	Time on code (secs)	% total time	Elapsed time (secs)	Cumulative %
RBRF	46	2.5	46	2.5
GEN	10	0.5	56	3.0
GEN/DRAW	61	3.3	117	6.3
GEN	5	0.3	122	6.6
PPR	10	0.5	132	7.1
MPR	11	0.6	143	7.7
RBRF	19	1.0	162	8.7
DCONS	24	1.3	186	10.0
MPR	84	4.5	270	14.5
TPR	2	0.1	272	14.6
DRAW	27	1.5	299	16.1
EDRAW	40	2.1	339	18.2
MPR	23	1.2	362	19.5
PPR	43	2.3	405	21.8
MPR	24	1.3	429	23.1
PPR	19	1.0	448	24.1
ARM	9	0.5	457	24.6
GEN	22	1.2	479	25.7
MPR	29	1.6	508	27.3
TPR	16	0.9	524	28.2
ABAN	2	0.1	526	28.3
GEN	4	0.2	530	28.5
ARM	2	0.1	532	28.6
GEN	8	0.4	540	29.0
MODPR	20	1.1	560	30.1
MODPR	9	0.5	569	30.6
GEN/MANIP	62	3.3	631	33.9
MPR	34	1.8	665	35.7
TPR	8	0.4	673	36.2
IPPR	17	0.9	690	37.1
ARM	15	0.8	705	37.9
MPR	107	5.7	812	43.6
TPR	5	0.3	817	43.9
MPR	24	1.3	841	45.2
TPR	8	0.4	849	45.6
MODPR	3	0.2	852	45.8
MPR	45	2.4	897	48.2
TPR	12	0.6	909	48.8

Data for graph of Dyad 2

MODPR	5	0.3	914	49.1
TPR	6	0.3	920	49.4
MANIP	70	3.8	990	53.2
MODPR	35	1.9	1025	55.1
MANIP	7	0.4	1032	55.5
MODPR	60	3.2	1092	58.7
TPR	22	1.2	1114	59.9
MANIP	9	0.5	1123	60.3
MODPR	21	1.1	1144	61.5
TPR	5	0.3	1149	61.7
MODPR	26	1.4	1175	63.1
MANIP	16	0.9	1191	64.0
DCONS	2	0.1	1193	64.1
MODPR	93	5.0	1286	69.1
TPR	6	0.3	1292	69.4
MODPR	48	2.6	1340	72.0
IPPR	8	0.4	1348	72.4
MODPR	45	2.4	1393	74.9
EPR	11	0.6	1404	75.4
MODPR	20	1.1	1424	76.5
TPR	7	0.4	1431	76.9
MODPR	30	1.6	1461	78.5
EPR	4	0.2	1465	78.7
MODPR	76	4.1	1541	82.8
EPR	65	3.5	1606	86.3
MODPR	51	2.7	1657	89.0
EPR	39	2.1	1696	91.1
MODPR	14	0.8	1710	91.9
EPR	30	1.6	1740	93.5
DCONS	2	0.1	1742	93.6
IPPR	14	0.8	1756	94.4
MODPR	29	1.6	1785	95.9
EPR	65	3.5	1850	99.4
RRPR	9	0.5	1859	99.9
RRPR	2	0.1	1861	100.0

Data for graph of Dyad 3

Code	Time on code (secs)	% total time	Elapsed time (secs)	Cumulative %
RBRF	44	5.9	44	5.9
GEN	2	0.3	46	6.2
GEN	10	1.3	56	7.5
MANIP	6	0.8	62	8.3
GEN/DRAW	46	6.2	108	14.5
RBRF	4	0.5	112	15.0
MANIP	2	0.3	114	15.3
DRAW	4	0.5	118	15.8
GEN/MANIP	38	5.1	156	20.9
GEN	12	1.6	168	22.6
PMU	5	0.7	173	23.2
MMU	58	7.8	231	31.0
TMU	2	0.3	233	31.3
MMU	21	2.8	254	34.1
EMU	13	1.7	267	35.8
RMU	9	1.2	276	37.0
EMU	5	0.7	281	37.7
MPR	63	8.5	344	46.2
ARM	23	3.1	367	49.3
MPR	23	3.1	390	52.3
IPPR	1	0.1	391	52.5
EPR	9	1.2	400	53.7
MODPR	27	3.6	427	57.3
EPR	5	0.7	432	58.0
IPPR	10	1.3	442	59.3
EPR	11	1.5	453	60.8
MODPR	38	5.1	491	65.9
ARM	8	1.1	499	67.0
MODPR	9	1.2	508	68.2
ARM	2	0.3	510	68.5
MPR	9	1.2	519	69.7
IPPR	12	1.6	531	71.3
MODPR	20	2.7	551	74.0
ARM	8	1.1	559	75.0
IPPR	3	0.4	562	75.4
EPR	15	2.0	577	77.4
MODPR	22	3.0	599	80.4
IPPR	12	1.6	611	82.0

Data for graph of Dyad 3

MODPR	6	0.8	617	82.8
EPR	27	3.6	644	86.4
IPPR	2	0.3	646	86.7
MODPR	7	0.9	653	87.7
EPR	80	10.7	733	98.4
RRPR	12	1.6	745	100.0

Data for graph of Dyad 4

Codes	Time on code (secs)	% total time	Elapsed time (secs)	Cumulative %
RBRF	47	1.3	47	1.3
ARM	8	0.2	55	1.5
GEN/MANIP	54	1.5	109	3.0
MMU	3	0.1	112	3.0
GEN	2	0.1	114	3.1
EMU	25	0.7	139	3.8
RBRF	15	0.4	154	4.2
EMU	17	0.5	171	4.6
GEN	21	0.6	192	5.2
MMU	58	1.6	250	6.8
EMU	6	0.2	256	7.0
RMU	6	0.2	262	7.1
EMU	2	0.1	264	7.2
RMU	4	0.1	268	7.3
EMU	31	0.8	299	8.1
RRMU	13	0.4	312	8.5
GEN	7	0.2	319	8.7
MMU	58	1.6	377	10.2
TMU	8	0.2	385	10.5
RMU	2	0.1	387	10.5
TMU	4	0.1	391	10.6
RMU	63	1.7	454	12.3
TMU	14	0.4	468	12.7
RMU	21	0.6	489	13.3
EMU	12	0.3	501	13.6
RRMU	8	0.2	509	13.8
GEN	20	0.5	529	14.4
PMU	39	1.1	568	15.4
MMU	51	1.4	619	16.8
ARM	22	0.6	641	17.4
PMU	5	0.1	646	17.5
MMU	33	0.9	679	18.4
TMU	19	0.5	698	19.0
PMU	12	0.3	710	19.3
MMU	12	0.3	722	19.6
RMU	3	0.1	725	19.7
MMU	9	0.2	734	19.9
TMU	15	0.4	749	20.3

Data for graph of Dyad 4

MMU	12	0.3	761	20.7
TMU	7	0.2	768	20.9
RMU	20	0.5	788	21.4
TMU	3	0.1	791	21.5
RMU	18	0.5	809	22.0
TMU	9	0.2	818	22.2
MMU	2	0.1	820	22.3
EMU	4	0.1	824	22.4
RMU	33	0.9	857	23.3
EMU	11	0.3	868	23.6
RMU	41	1.1	909	24.7
EMU	22	0.6	931	25.3
RMU	14	0.4	945	25.7
EMU	7	0.2	952	25.8
ABAN	11	0.3	963	26.1
GEN	22	0.6	985	26.7
RBRF	8	0.2	993	27.0
GEN	23	0.6	1016	27.6
RMU	43	1.2	1059	28.8
PMU	19	0.5	1078	29.3
MMU	68	1.8	1146	31.1
PMU	3	0.1	1149	31.2
MMU	26	0.7	1175	31.9
EMU	18	0.5	1193	32.4
RRMU	32	0.9	1225	33.3
DPERF	49	1.3	1274	34.6
PMU	21	0.6	1295	35.2
MMU	10	0.3	1305	35.4
ARM	35	1.0	1340	36.4
ARM	58	1.6	1398	38.0
PMU	28	0.8	1426	38.7
ARM	11	0.3	1437	39.0
MMU	67	1.8	1504	40.8
TMU	2	0.1	1506	40.9
RMU	61	1.7	1567	42.5
PMU	8	0.2	1575	42.8
TMU	17	0.5	1592	43.2
PMU	5	0.1	1597	43.4
RMU	69	1.9	1666	45.2

Data for graph of Dyad 4

TMU	6	0.2	1672	45.4
PMU	24	0.7	1696	46.0
MMU	61	1.7	1757	47.7
TMU	4	0.1	1761	47.8
RMU	38	1.0	1799	48.8
TMU	10	0.3	1809	49.1
RMU	13	0.4	1822	49.5
TMU	69	1.9	1891	51.3
RMU	31	0.8	1922	52.2
TMU	34	0.9	1956	53.1
RMU	103	2.8	2059	55.9
TMU	19	0.5	2078	56.4
RMU	72	2.0	2150	58.4
TMU	11	0.3	2161	58.7
MMU	22	0.6	2183	59.3
EMU	8	0.2	2191	59.5
MMU	41	1.1	2232	60.6
EMU	17	0.5	2249	61.1
DCONS	3	0.1	2252	61.1
RMU	18	0.5	2270	61.6
EMU	14	0.4	2284	62.0
RMU	26	0.7	2310	62.7
EMU	21	0.6	2331	63.3
DCONS	10	0.3	2341	63.6
RRMU	11	0.3	2352	63.9
ARM	69	1.9	2421	65.7
MPR	17	0.5	2438	66.2
TPR	5	0.1	2443	66.3
MPR	8	0.2	2451	66.5
TPR	18	0.5	2469	67.0
ARM	27	0.7	2496	67.8
PPR	12	0.3	2508	68.1
MPR	70	1.9	2578	70.0
TPR	12	0.3	2590	70.3
MODPR	20	0.5	2610	70.9
TPR	3	0.1	2613	70.9
MODPR	70	1.9	2683	72.8
MPR	33	0.9	2716	73.7
MODPR	13	0.4	2729	74.1

Data for graph of Dyad 4

TPR	10	0.3	2739	74.4
MODPR	42	1.1	2781	75.5
ARM	11	0.3	2792	75.8
MODPR	81	2.2	2873	78.0
EPR	9	0.2	2882	78.3
MODPR	14	0.4	2896	78.6
EPR	10	0.3	2906	78.9
MODPR	8	0.2	2914	79.1
EPR	35	1.0	2949	80.1
MODPR	29	0.8	2978	80.9
EPR	10	0.3	2988	81.1
MODPR	11	0.3	2999	81.4
EPR	25	0.7	3024	82.1
MPR	24	0.7	3048	82.8
ARM	6	0.2	3054	82.9
MPR	43	1.2	3097	84.1
EPR	35	1.0	3132	85.0
MODPR	32	0.9	3164	85.9
EPR	53	1.4	3217	87.3
MODPR	19	0.5	3236	87.9
EPR	11	0.3	3247	88.2
MODPR	17	0.5	3264	88.6
EPR	28	0.8	3292	89.4
MODPR	10	0.3	3302	89.7
EPR	8	0.2	3310	89.9
MODPR	143	3.9	3453	93.8
EPR	28	0.8	3481	94.5
MODPR	92	2.5	3573	97.0
EPR	15	0.4	3588	97.4
MODPR	35	1.0	3623	98.4
EPR	27	0.7	3650	99.1
RRPR	33	0.9	3683	100.0

Data for graph of Dyad 5

Codes	Time on codes (secs)	% total time	Elapsed time (secs)	Cumulative %
RBRF	60	2.0	60	2.0
GEN	72	2.4	132	4.3
DRAW	7	0.2	139	4.6
GEN/MANIP	60	2.0	199	6.6
ARM	37	1.2	236	7.8
MMU	43	1.4	279	9.2
TMU	7	0.2	286	9.4
GEN	20	0.7	306	10.1
MMU	7	0.2	313	10.3
PMU	3	0.1	316	10.4
MMU	100	3.3	416	13.7
PMU	22	0.7	438	14.4
RMU	17	0.6	455	15.0
ARM	30	1.0	485	16.0
MMU	199	6.6	684	22.5
EMU	22	0.7	706	23.2
RMU	66	2.2	772	25.4
EMU	15	0.5	787	25.9
RMU	43	1.4	830	27.3
EMU	20	0.7	850	28.0
RMU	22	0.7	872	28.7
ABAN	7	0.2	879	28.9
EMU	2	0.1	881	29.0
GEN	9	0.3	890	29.3
ARM	35	1.2	925	30.5
GEN/DRAW	51	1.7	976	32.1
MANIP	4	0.1	980	32.3
GEN	16	0.5	996	32.8
DRAW	6	0.2	1002	33.0
MMU	3	0.1	1005	33.1
GEN	14	0.5	1019	33.6
MMU	176	5.8	1195	39.3
TMU	3	0.1	1198	39.4
MMU	61	2.0	1259	41.5
DCONS	2	0.1	1261	41.5
MMU	49	1.6	1310	43.1
RMU	34	1.1	1344	44.3
TMU	53	1.7	1397	46.0

Data for graph of Dyad 5

MMU	86	2.8	1483	48.8
DPERF	10	0.3	1493	49.2
RMU	15	0.5	1508	49.7
TMU	16	0.5	1524	50.2
RMU	5	0.2	1529	50.3
MMU	167	5.5	1696	55.8
EMU	65	2.1	1761	58.0
RMU	29	1.0	1790	58.9
ARM	3	0.1	1793	59.0
RMU	68	2.2	1861	61.3
EMU	54	1.8	1915	63.1
RMU	20	0.7	1935	63.7
ARM	2	0.1	1937	63.8
MMU	11	0.4	1948	64.1
EMU	59	1.9	2007	66.1
RMU	14	0.5	2021	66.5
ABAN	11	0.4	2032	66.9
RBRF	13	0.4	2045	67.3
GEN/MANIP	17	0.6	2062	67.9
ARM	19	0.6	2081	68.5
MMU	59	1.9	2140	70.5
TMU	20	0.7	2160	71.1
GEN	37	1.2	2197	72.3
GEN/MANIP	21	0.7	2218	73.0
MMU	60	2.0	2278	75.0
TMU	3	0.1	2281	75.1
RMU	69	2.3	2350	77.4
TMU	1	0.0	2351	77.4
RMU	306	10.1	2657	87.5
PPR	13	0.4	2670	87.9
MPR	14	0.5	2684	88.4
PPR	18	0.6	2702	89.0
MPR	79	2.6	2781	91.6
TPR	8	0.3	2789	91.8
MPR	218	7.2	3007	99.0
EPR	30	1.0	3037	100.0

APPENDIX K - FREQUENCY OF CODES FOR EACH DYAD

Frequency of codes for each dyad

	A	B	C	D	E	F	G	H
1	Step	Code	Dyad 1	Dyad 2	Dyad 3	Dyad 4	Dyad 5	Total
2	Understand	RBRF	2	2	2	3	2	11
3	Understand	DPERF	2	0	0	1	1	4
4	Understand	DCONS	3	3	0	0	1	7
5	Generate	GEN	6	7	5	7	10	35
6	Generate	DRAW	3	2	2	0	3	10
7	Generate	G/DRAW	2	1	0	0	1	4
8	Generate	G/MAN	1	1	0	1	3	6
9	Model	PMU	0	0	1	10	2	13
10	Model	MANIP	4	5	3	1	4	17
11	Model	MMU	7	0	2	16	13	38
12	Model	RMU	14	0	1	21	13	49
13	Model	CMMU	0	0	0	1	0	1
14	Model	ARM	6	3	4	9	6	28
15	Model	ABAN	0	1	0	1	2	4
16	Build	PPR	0	3	0	1	2	6
17	Build	MPR	3	9	3	6	3	24
18	Build	IPPR	0	3	6	0	0	9
19	Build	MODPR	1	17	7	16	0	41
20	Evaluate	EGEN	0	0	0	0	0	0
21	Evaluate	EDRAW	0	1	0	0	0	1
22	Evaluate	TMU	3	0	1	17	7	28
23	Evaluate	EMU	10	0	2	15	7	34
24	Evaluate	TPR	1	11	0	5	1	18
25	Evaluate	EPR	6	6	6	13	1	32
26	Evaluate	RRMU	0	0	0	4	0	4
27	Evaluate	RRPR	0	2	1	1	0	4
28	Miscellan.	FS	1	0	1	0	1	3
29	Miscellan.	OTT	1	3	1	1	0	6
30	Miscellan.	BM	14	4	4	6	8	36
31	Miscellan.	CR	2	0	4	0	4	10
32	Miscellan.	RCR	1	1	5	0	4	11
33	Miscellan.	WU	3	2	2	2	0	9
34	Miscellan.	RINTRO	4	4	4	1	5	18
35	Miscellan.	RC	9	5	4	5	3	26
36	Total		109	96	71	164	107	547

APPENDIX L - SEQUENCE OF STEPS EMPLOYED BY EACH DYAD

Sequence of steps employed by Dyad 1

Step	Time on step (secs)	% total time	Cumulative %
Understand	49	2.5	2.5
Generate	98	5.0	7.5
Understand	18	0.9	8.5
Model	177	9.1	17.5
Evaluate	16	0.8	18.4
Model	20	1.0	19.4
Evaluate	23	1.2	20.6
Model	27	1.4	21.9
Evaluate	2	0.1	22.1
Model	100	5.1	27.2
Evaluate	30	1.5	28.7
Model	15	0.8	29.5
Evaluate	8	0.4	29.9
Understand	14	0.7	30.6
Model	11	0.6	31.2
Evaluate	6	0.3	31.5
Model	17	0.9	32.4
Evaluate	5	0.3	32.6
Model	87	4.5	37.1
Evaluate	25	1.3	38.4
Model	29	1.5	39.8
Understand	2	0.1	39.9
Model	36	1.8	41.8
Evaluate	70	3.6	45.4
Model	17	0.9	46.3
Evaluate	4	0.2	46.5
Model	90	4.6	51.1
Evaluate	25	1.3	52.4
Model	79	4.1	56.4
Evaluate	8	0.4	56.8
Model	7	0.4	57.2
Build	26	1.3	58.5
Model	49	2.5	61.0
Understand	10	0.5	61.5
Evaluate	22	1.1	62.7
Generate	22	1.1	63.8
Model	332	17.0	80.8
Evaluate	32	1.6	82.5

Sequence of steps employed by Dyad 1

Model	20	1.0	83.5
Understand	24	1.2	84.7
Build	89	4.6	89.3
Evaluate	10	0.5	89.8
Build	70	3.6	93.4
Evaluate	34	1.7	95.1
Build	34	1.7	96.9
Evaluate	61	3.1	100.0

Sequence of steps employed by Dyad 2

Step	Time on step (secs)	% total time	Cumulative %
Understand	46	2.5	2.5
Generate	76	4.1	6.6
Build	21	1.1	7.7
Understand	43	2.3	10.0
Build	84	4.5	14.5
Evaluate	2	0.1	14.6
Generate	27	1.5	16.1
Evaluate	40	2.1	18.2
Build	109	5.9	24.1
Model	9	0.5	24.6
Generate	22	1.2	25.7
Build	29	1.6	27.3
Evaluate	16	0.9	28.2
Model	2	0.1	28.3
Generate	4	0.2	28.5
Model	2	0.1	28.6
Generate	8	0.4	29.0
Build	29	1.6	30.6
Generate	62	3.3	33.9
Build	34	1.8	35.7
Evaluate	8	0.4	36.2
Build	17	0.9	37.1
Model	15	0.8	37.9
Build	107	5.7	43.6
Evaluate	5	0.3	43.9
Build	24	1.3	45.2
Evaluate	8	0.4	45.6
Build	48	2.6	48.2
Evaluate	12	0.6	48.8
Build	5	0.3	49.1
Evaluate	6	0.3	49.4
Model	70	3.8	53.2
Build	35	1.9	55.1
Model	7	0.4	55.5

Sequence of steps employed by Dyad 2

Build	60	3.2	58.7
Evaluate	22	1.2	59.9
Model	9	0.5	60.3
Build	21	1.1	61.5
Evaluate	5	0.3	61.7
Build	26	1.4	63.1
Model	16	0.9	64.0
Understand	2	0.1	64.1
Build	93	5.0	69.1
Evaluate	6	0.3	69.4
Build	101	5.4	74.9
Evaluate	11	0.6	75.4
Build	20	1.1	76.5
Evaluate	7	0.4	76.9
Build	30	1.6	78.5
Evaluate	4	0.2	78.7
Build	76	4.1	82.8
Evaluate	65	3.5	86.3
Build	51	2.7	89.0
Evaluate	39	2.1	91.1
Build	14	0.8	91.9
Evaluate	30	1.6	93.5
Understand	2	0.1	93.6
Build	43	2.3	95.9
Evaluate	76	4.1	100.0

Sequence of steps employed by Dyad 3

Step	Time on step (secs)	% total time	Cumulative %
Understand	44	5.9	5.9
Generate	12	1.6	7.5
Model	6	0.8	8.3
Generate	46	6.2	14.5
Understand	4	0.5	15.0
Model	2	0.3	15.3
Generate	54	7.2	22.6
Model	63	8.5	31.0
Evaluate	2	0.3	31.3
Model	21	2.8	34.1
Evaluate	13	1.7	35.8
Model	9	1.2	37.0
Evaluate	5	0.7	37.7
Model	86	11.5	49.3
Build	24	3.2	52.5
Evaluate	9	1.2	53.7
Build	27	3.6	57.3
Evaluate	5	0.7	58.0
Build	10	1.3	59.3
Evaluate	11	1.5	60.8
Build	38	5.1	65.9
Model	8	1.1	67.0
Build	9	1.2	68.2
Model	2	0.3	68.5
Build	41	5.5	74.0
Model	8	1.1	75.0
Build	3	0.4	75.4
Evaluate	15	2.0	77.4
Build	40	5.4	82.8
Evaluate	27	3.6	86.4
Build	9	1.2	87.7
Evaluate	92	12.3	100.0

Sequence of steps employed by Dyad 4

Step	Time on step (secs)	% total time	Cumulative %
Understand	47	1.3	1.3
Model	8	0.2	1.5
Generate	54	1.5	3.0
Model	3	0.1	3.0
Generate	2	0.1	3.1
Evaluate	25	0.7	3.8
Understand	15	0.4	4.2
Evaluate	17	0.5	4.6
Generate	21	0.6	5.2
Model	58	1.6	6.8
Evaluate	6	0.2	7.0
Model	6	0.2	7.1
Evaluate	2	0.1	7.2
Model	4	0.1	7.3
Evaluate	44	1.2	8.5
Generate	7	0.2	8.7
Model	58	1.6	10.2
Evaluate	8	0.2	10.5
Model	2	0.1	10.5
Evaluate	4	0.1	10.6
Model	63	1.7	12.3
Evaluate	14	0.4	12.7
Model	21	0.6	13.3
Evaluate	20	0.5	13.8
Generate	20	0.5	14.4
Model	150	4.1	18.4
Evaluate	19	0.5	19.0
Model	36	1.0	19.9
Evaluate	15	0.4	20.3
Model	12	0.3	20.7
Evaluate	7	0.2	20.9
Model	20	0.5	21.4
Evaluate	3	0.1	21.5
Model	18	0.5	22.0
Evaluate	9	0.2	22.2
Model	2	0.1	22.3
Evaluate	4	0.1	22.4
Model	33	0.9	23.3

Sequence of steps employed by Dyad 4

Evaluate	11	0.3	23.6
Model	41	1.1	24.7
Evaluate	22	0.6	25.3
Model	14	0.4	25.7
Evaluate	7	0.2	25.8
Model	11	0.3	26.1
Generate	22	0.6	26.7
Understand	8	0.2	27.0
Generate	23	0.6	27.6
Model	159	4.3	31.9
Evaluate	50	1.4	33.3
Understand	49	1.3	34.6
Model	230	6.2	40.8
Evaluate	2	0.1	40.9
Model	69	1.9	42.8
Evaluate	17	0.5	43.2
Model	74	2.0	45.2
Evaluate	6	0.2	45.4
Model	85	2.3	47.7
Evaluate	4	0.1	47.8
Model	38	1.0	48.8
Evaluate	10	0.3	49.1
Model	13	0.4	49.5
Evaluate	69	1.9	51.3
Model	31	0.8	52.2
Evaluate	34	0.9	53.1
Model	103	2.8	55.9
Evaluate	19	0.5	56.4
Model	72	2.0	58.4
Evaluate	11	0.3	58.7
Model	22	0.6	59.3
Evaluate	8	0.2	59.5
Model	41	1.1	60.6
Evaluate	17	0.5	61.1
Understand	3	0.1	61.1
Model	18	0.5	61.6
Evaluate	14	0.4	62.0
Model	26	0.7	62.7
Evaluate	21	0.6	63.3

Sequence of steps employed by Dyad 4

Understand	10	0.3	63.6
Evaluate	11	0.3	63.9
Model	69	1.9	65.7
Build	17	0.5	66.2
Evaluate	5	0.1	66.3
Build	8	0.2	66.5
Evaluate	18	0.5	67.0
Model	27	0.7	67.8
Build	82	2.2	70.0
Evaluate	12	0.3	70.3
Build	20	0.5	70.9
Evaluate	3	0.1	70.9
Build	116	3.1	74.1
Evaluate	10	0.3	74.4
Build	42	1.1	75.5
Model	11	0.3	75.8
Build	81	2.2	78.0
Evaluate	9	0.2	78.3
Build	14	0.4	78.6
Evaluate	10	0.3	78.9
Build	8	0.2	79.1
Evaluate	35	1.0	80.1
Build	29	0.8	80.9
Evaluate	10	0.3	81.1
Build	11	0.3	81.4
Evaluate	25	0.7	82.1
Build	24	0.7	82.8
Model	6	0.2	82.9
Build	43	1.2	84.1
Evaluate	35	1.0	85.0
Build	32	0.9	85.9
Evaluate	53	1.4	87.3
Build	19	0.5	87.9
Evaluate	11	0.3	88.2
Build	17	0.5	88.6
Evaluate	28	0.8	89.4
Build	10	0.3	89.7
Evaluate	8	0.2	89.9
Build	143	3.9	93.8

Sequence of steps employed by Dyad 4

Evaluate	28	0.8	94.5
Build	92	2.5	97.0
Evaluate	15	0.4	97.4
Build	35	1.0	98.4
Evaluate	60	1.6	100.0

Sequence of steps employed by Dyad 5

Step	Time on step (secs)	% total time	Cumulative %
Understand	60	2.0	2.0
Generate	139	4.6	6.6
Model	80	2.6	9.2
Evaluate	7	0.2	9.4
Generate	20	0.7	10.1
Model	378	12.4	22.5
Evaluate	22	0.7	23.2
Model	66	2.2	25.4
Evaluate	15	0.5	25.9
Model	43	1.4	27.3
Evaluate	20	0.7	28.0
Model	29	1.0	28.9
Evaluate	2	0.1	29.0
Generate	9	0.3	29.3
Model	35	1.2	30.5
Generate	51	1.7	32.1
Model	4	0.1	32.3
Generate	22	0.7	33.0
Model	3	0.1	33.1
Generate	14	0.5	33.6
Model	176	5.8	39.3
Evaluate	3	0.1	39.4
Model	61	2.0	41.5
Understand	2	0.1	41.5
Model	83	2.7	44.3
Evaluate	53	1.7	46.0
Model	86	2.8	48.8
Understand	10	0.3	49.2
Model	15	0.5	49.7
Evaluate	16	0.5	50.2
Model	172	5.7	55.8
Evaluate	65	2.1	58.0
Model	100	3.3	61.3
Evaluate	54	1.8	63.1
Model	33	1.1	64.1
Evaluate	59	1.9	66.1
Model	25	0.8	66.9
Understand	13	0.4	67.3

Sequence of steps employed by Dyad 5

Generate	17	0.6	67.9
Model	78	2.6	70.5
Evaluate	20	0.7	71.1
Generate	58	1.9	73.0
Model	60	2.0	75.0
Evaluate	3	0.1	75.1
Model	69	2.3	77.4
Evaluate	1	0.0	77.4
Model	306	10.1	87.5
Build	124	4.1	91.6
Evaluate	8	0.3	91.8
Build	218	7.2	99.0
Evaluate	30	1.0	100.0

APPENDIX M - DATA ENTERED INTO SPREADSHEETS

Spreadsheet entry of data for graph of Task 1

	A	B	C	D	E	F	G	H	I	J	K	L
1	% data task 1	0	2.5	4.4	5.1	5.6	5.9	7.1	7.5	8.5	9.1	9.399
2	RBRF	2	2									
3	DPERF											
4	DCONS								4	4		
5	GEN			5	5	5	5	5	5			
6	DRAW		6	6	6		6	6				
7	PMU											
8	MANIP					8	8					
9	MMU										9	9
10	RMU											
11	CMMU											
12	ARM									12	12	
13	ABAN											
14	PPR											
15	MPR											
16	IPPR											
17	MODPR											
18	EGEN											
19	EDRAW											
20	TMU											
21	EMU											
22	TPR											
23	EPR											
24	RRMU											
25	RRPR											

Spreadsheet entry of data for graph of Task 1

	M	N	O	P	Q	R	S	T	U	V	W	X	Y
1	9.4	9.5	12	16.5	17.5	18.399	18.4	19.399	19.4	20.599	20.6	21.899	21.9
2													
3													
4													
5													
6													
7													
8													
9	9		9	9									
10				10	10		10	10	10		10	10	10
11													
12	12	12	12										
13													
14													
15													
16													
17													
18													
19													
20					20	20	20		20	20	20		20
21													
22													
23													
24													
25													

Spreadsheet entry of data for graph of Task 1

	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL
1	22.1	27.2	28.7	29.499	29.5	29.9	30.3	30.6	31.2	31.499	31.5	32.399	32.4
2						2	2						
3							3	3					
4													
5													
6													
7													
8													
9	9	9											
10			10	10	10			10	10		10	10	10
11													
12													
13													
14													
15													
16													
17													
18													
19													
20	20												
21		21	21		21	21			21	21	21		21
22													
23													
24													
25													

Spreadsheet entry of data for graph of Task 1

	AM	AN	AO	AP	AQ	AR	AS	AT	AU	AV	AW	AX	AY
1	32.599	32.6	37.099	37.1	38.399	38.4	39.8	39.899	39.9	41.8	45.399	45.4	46.299
2													
3													
4							4	4	4				
5													
6													
7													
8													
9													
10		10	10	10		10	10		10	10		10	10
11													
12													
13													
14													
15													
16													
17													
18													
19													
20													
21	21	21		21	21	21				21	21	21	
22													
23													
24													
25													

Spreadsheet entry of data for graph of Task 1

	AZ	BA	BB	BC	BD	BE	BF	BG	BH	BI	BJ	BK	BL
1	46.3	46.499	46.5	50.1	50.299	50.3	51.1	52.399	52.4	52.9	56.4	56.8	57.2
2													
3													
4													
5													
6													
7													
8				8	8	8							
9										9	9		
10	10		10	10		10	10		10	10			
11													
12												12	12
13													
14													
15													15
16													
17													
18													
19													
20													
21	21	21	21				21	21	21		21	21	
22													
23													
24													
25													

Spreadsheet entry of data for graph of Task 1

	BM	BN	BO	BP	BQ	BR	BS	BT	BU	BV	BW	BX	BY
1	58.5	61	61.499	61.5	62	62.7	63.8	66.5	67.2	68.399	68.4	69.799	69.8
2													
3		3	3	3									
4													
5						5	5						
6													
7													
8								8	8		8	8	8
9									9	9	9		9
10													
11													
12							12	12					
13													
14													
15	15												
16													
17													
18													
19													
20													
21													
22													
23	23	23		23	23	23							
24													
25													

Spreadsheet entry of data for graph of Task 1

	BZ	CA	CB	CC	CD	CE	CF	CG	CH	CI	CJ	CK	CL
1	73.5	75.699	75.7	80.8	82.5	83.5	84.7	89.3	89.799	89.8	93.4	95.1	96.899
2													
3													
4						4	4						
5													
6													
7													
8													
9	9		9	9									
10	10	10	10										
11													
12					12	12							
13													
14													
15							15	15		15	15		
16													
17												17	17
18													
19													
20													
21				21	21								
22								22	22	22			
23											23	23	
24													
25													

Spreadsheet entry of data for graph of Task 1

	CM	CN	CO
1	96.9	98.4	100
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
16			
17	17		
18			
19			
20			
21			
22			
23	23	23	23
24			
25			

Spreadsheet entry of data for graph of Task 2

% data task 2	0	2.5	3	6.3	6.6	7.1	7.7	8.7	10	14.5	14.6	16.1
RBRF	2	2					2	2				
DPERF												
DCONS								4	4			
GEN		5	5	5	5							
DRAW			6	6							6	6
PMU												
MANIP												
MMU												
RMU												
CMMU												
ARM												
ABAN												
PPR					14	14						
MPR						15	15		15	15		
IPPR												
MODPR												
EGEN												
EDRAW												19
TMU												
EMU												
TPR										22	22	
EPR												
RRMU												
RRPR												

Spreadsheet entry of data for graph of Task 2

18.2	19.5	21.799	21.8	23.099	23.1	24.1	24.6	25.7	27.3	28.2	28.3	28.5
							5	5			5	5
						12	12					12
										13	13	
	14	14	14		14	14						
15	15		15	15	15			15	15			
19												
									22	22		

Spreadsheet entry of data for graph of Task 2

28.599	28.6	29	30.1	30.6	33.9	35.7	36.2	37.1	37.9	43.6	43.899	43.9
	5	5		5	5							
				8	8							
12	12							12	12			
					15	15			15	15		15
							16	16				
		17	17	17								
						22	22			22	22	22

Spreadsheet entry of data for graph of Task 2

45.199	45.2	45.6	45.8	48.2	48.8	49.099	49.1	49.4	53.2	55.099	55.1	55.499
								8	8		8	8
15	15		15	15								
		17	17		17	17	17		17	17	17	
	22	22		22	22		22	22				

Spreadsheet entry of data for graph of Task 2

55.5	58.7	59.9	60.3	61.5	61.699	61.7	63.1	64	64.1	69.1	69.399	69.4
								4	4			
8		8	8				8	8				
17	17		17	17		17	17		17	17		17
	22	22		22	22	22				22	22	22

Spreadsheet entry of data for graph of Task 2

72	72.399	72.4	74.9	75.399	75.4	76.5	76.899	76.9	78.5	78.699	78.7	82.799
16	16	16										
17		17	17		17	17		17	17		17	17
						22	22	22				
			23	23	23				23	23	23	

Spreadsheet entry of data for graph of Task 2

82.8	86.299	86.3	88.999	89	91.099	91.1	91.899	91.9	93.5	93.6	94.4	95.9
									4	4		
										16	16	
17		17	17	17		17	17	17			17	17
23	23	23		23	23	23		23	23			23

Spreadsheet entry of data for graph of Task 2

99.4	99.9	100
23		
25	25	25

Spreadsheet entry of data for graph of Task 3

% data task 3	0	5.9	6.2	7.5	8.299	8.3	14.5	15	15.3	15.799	15.8	20.9
RBRF	2	2					2	2				
DPERF												
DCONS												
GEN		5	5	5		5	5				5	5
DRAW						6	6		6	6	6	
PMU												
MANIP				8	8	8		8	8		8	8
MMU												
RMU												
CMMU												
ARM												
ABAN												
PPR												
MPR												
IPPR												
MODPR												
EGEN												
EDRAW												
TMU												
EMU												
TPR												
EPR												
RRMU												
RRPR												

Spreadsheet entry of data for graph of Task 3

22.6	23.2	31	31.299	31.3	34.1	35.8	36.999	37	37.7	46.2	49.299	49.3
5												
7	7											
	9	9		9	9							
						10	10	10				
										12	12	12
									15	15		15
		20	20	20								
					21	21		21	21			

Spreadsheet entry of data for graph of Task 3

52.3	52.5	53.7	57.299	57.3	58	59.299	59.3	60.8	65.9	66.999	67	68.199
									12	12	12	
15												
16	16				16	16	16					
		17	17	17				17	17		17	17
	23	23		23	23		23	23				

Spreadsheet entry of data for graph of Task 3

68.2	68.5	69.7	71.3	74	75	75.4	77.4	80.4	81.999	82	82.8	86.4
12	12			12	12							
	15	15										
		16	16		16	16		16	16	16		16
17			17	17			17	17		17	17	
						23	23				23	23

Spreadsheet entry of data for graph of Task 3

86.7	87.7	98.4	100
16			
17	17		
	23	23	
		25	25

Spreadsheet entry of data for graph of Task 4

% data task 4	0	1.3	1.5	3	3.099	3.1	3.2	3.8	4.199	4.2	4.6	5.2
RBRF	2	2						2	2	2		
DPERF												
DCONS												
GEN			5	5		5	5				5	5
DRAW												
PMU												
MANIP			8	8								
MMU				9	9	9						9
RMU												
CMMU												
ARM		12	12									
ABAN												
PPR												
MPR												
IPPR												
MODPR												
EGEN												
EDRAW												
TMU												
EMU							21	21		21	21	
TPR												
EPR												
RRMU												
RRPR												

Spreadsheet entry of data for graph of Task 4

6.8	7	7.099	7.1	7.199	7.2	7.299	7.3	8.1	8.5	8.7	10.2	10.4
									5	5		
9										9	9	
	10	10	10		10	10	10					10
											20	20
21	21		21	21	21		21	21				
								24	24			

Spreadsheet entry of data for graph of Task 4

10.499	10.5	10.599	10.6	12.299	12.3	12.699	12.7	13.3	13.6	13.8	14.4	15.4
										5	5	
											7	7
												9
10	10		10	10	10		10	10				
	20	20	20		20	20	20					
								21	21			
									24	24		

Spreadsheet entry of data for graph of Task 4

16.8	17.4	17.5	18.4	19	19.3	19.6	19.699	19.7	19.9	20.299	20.3	20.699
	7	7		7	7							
9		9	9		9	9		9	9		9	9
						10	10	10				
12	12											
			20	20					20	20	20	

Spreadsheet entry of data for graph of Task 4

20.7	20.9	21.399	21.4	21.499	21.5	21.999	22	22.2	22.3	22.4	23.299	23.3
9								9	9			
	10	10	10		10	10	10			10	10	10
20	20		20	20	20		20	20				
									21	21		21

Spreadsheet entry of data for graph of Task 4

23.599	23.6	24.699	24.7	25.299	25.3	25.699	25.7	25.8	26.1	26.7	26.999	27
										2	2	2
									5	5		5
	10	10	10		10	10	10					
								13	13			
21	21		21	21	21		21	21				

Spreadsheet entry of data for graph of Task 4

27.6	28.8	29.3	31.099	31.1	31.199	31.2	31.9	32.4	33.3	34.6	35.2	35.4
									3	3		
5												
	7	7		7	7	7				7	7	
		9	9	9		9	9				9	9
10	10											
												12
							21	21				
								24	24			

Spreadsheet entry of data for graph of Task 4

36.4	38	38.699	38.7	39	40.8	40.9	42.5	42.8	43.199	43.2	43.4	45.2
	7	7	7				7	7		7	7	
				9	9							
						10	10				10	10
12	12		12	12								
					20	20		20	20	20		20

Spreadsheet entry of data for graph of Task 4

45.4	46	47.7	47.8	48.799	48.8	49.099	49.1	49.499	49.5	51.299	51.3	52.199
7	7											
	9	9										
			10	10	10		10	10	10		10	10
20		20	20		20	20	20		20	20	20	

Spreadsheet entry of data for graph of Task 4

52.2	53.099	53.1	55.899	55.9	56.399	56.4	58.399	58.4	58.7	59.3	59.499	59.5
									9	9		9
10		10	10	10		10	10	10				
20	20	20		20	20	20		20	20			
										21	21	21

Spreadsheet entry of data for graph of Task 4

60.599	60.6	61.1	61.2	61.6	61.999	62	62.699	62.7	63.3	63.6	63.9	65.7
		4	4						4	4		
9	9											
			10	10		10	10	10				
											12	12
												15
	21	21		21	21	21		21	21			
										24	24	

Spreadsheet entry of data for graph of Task 4

66.2	66.299	66.3	66.499	66.5	67	67.8	68.1	70	70.3	70.799	70.8	70.899
					12	12						
						14	14					
15		15	15	15			15	15				
									17	17	17	
22	22	22		22	22			22	22		22	22

Spreadsheet entry of data for graph of Task 4

70.9	72.8	73.699	73.7	74.1	74.399	74.4	75.5	75.799	75.8	78	78.299	78.3
							12	12	12			
	15	15	15									
17	17		17	17		17	17		17	17		17
22				22	22	22						
										23	23	23

Spreadsheet entry of data for graph of Task 4

78.599	78.6	78.899	78.9	79.099	79.1	80.099	80.1	80.899	80.9	81.099	81.1	81.399
17	17		17	17	17		17	17	17		17	17
	23	23	23		23	23	23		23	23	23	

Spreadsheet entry of data for graph of Task 4

81.4	82.1	82.8	82.899	82.9	84.1	85	85.899	85.9	87.299	87.3	87.899	87.9
		12	12	12								
	15	15		15	15							
17						17	17	17		17	17	17
23	23				23	23		23	23	23		23

Spreadsheet entry of data for graph of Task 4

88.199	88.2	88.599	88.6	89.399	89.4	89.699	89.7	89.899	89.9	93.799	93.8	94.499
	17	17	17		17	17	17		17	17	17	
23	23		23	23	23		23	23	23		23	23

Spreadsheet entry of data for graph of Task 4

94.5	96.999	97	97.399	97.4	98.399	98.4	99.1	100
17	17	17		17	17	17		
23		23	23	23		23	23	
							25	25

Spreadsheet entry of data for graph of Task 5

%data task 5	0	2	4.3	4.599	4.6	6.6	7.8	9.2	9.4	10.1	10.3	10.399
RBRF	2	2										
DPERF												
DCONS												
GEN		5	5		5	5			5	5		
DRAW			6	6	6							
PMU											7	7
MANIP					8	8						
MMU							9	9		9	9	
RMU												
CMMU												
ARM						12	12					
ABAN												
PPR												
MPR												
IPPR												
MODPR												
EGEN												
EDRAW												
TMU								20	20			
EMU												
TPR												
EPR												
RRMU												
RRPR												

Spreadsheet entry of data for graph of Task 5

10.4	13.699	13.7	14.4	15	16	22.5	23.2	25.399	25.4	25.899	25.9	27.299
7		7	7									
9	9	9			9	9						
			10	10			10	10	10		10	10
				12	12							
						21	21		21	21	21	

Spreadsheet entry of data for graph of Task 5

27.3	27.999	28	28.7	28.9	29	29.3	30.499	30.5	32.1	32.299	32.3	32.8
					5	5		5	5		5	5
								6	6			6
									8	8	8	
10		10	10									
						12	12	12				
			13	13								
21	21	21		21	21							

Spreadsheet entry of data for graph of Task 5

33	33.1	33.599	33.6	39.3	39.399	39.4	41.5	41.599	41.6	43.1	44.3	46
							4	4	4			
	5	5	5									
6												
9	9		9	9		9	9		9	9		9
										10	10	
				20	20	20					20	20

Spreadsheet entry of data for graph of Task 5

48.8	49.2	49.7	50.199	50.2	50.3	55.8	58	58.9	58.999	59	61.3	63.099
3	3											
9					9	9						
	10	10		10	10		10	10		10	10	
								12	12	12		
		20	20	20								
						21	21				21	21

Spreadsheet entry of data for graph of Task 5

63.1	63.7	63.8	64.1	66.1	66.5	66.9	67.3	67.9	68.5	70.5	71.1	72.3
						2	2					
							5	5			5	5
							8	8				8
		9	9						9	9		
10	10			10	10							
	12	12						12	12			
					13	13						
										20	20	
21			21	21								

Spreadsheet entry of data for graph of Task 5

73	75	75.1	77.399	77.4	77.499	77.5	87.5	87.9	88.399	88.4	88.999	89
5												
8												
9	9											
		10	10	10		10	10					
							14	14		14	14	14
								15	15	15		15
	20	20		20	20	20						

Spreadsheet entry of data for graph of Task 5

91.6	91.799	91.8	99	100
15		15	15	
22	22	22		
			23	23

MCGILL UNIVERSITY

FACULTY OF EDUCATION

CERTIFICATE OF ETHICAL ACCEPTABILITY FOR RESEARCH INVOLVING HUMAN SUBJECTS

A review committee consisting of:

a). Professor H. Perrault

b). Professor J. Derevensky

c). Professor S. Nemiroff

has examined the application for certification of the ethical acceptability of the project titled:

Grade 7 students' conceptions of the design process within a technological context.

as proposed by:

Malcolm Welch (Applicant's Name)

Dr. John Gradwell (Supervisor's Name)

(Applicant's Signature)

(Supervisor's signature)

Granting agency: *Not applicable*

The review committee considers the research procedures, as explained by the applicant in this application, to be acceptable on ethical grounds.

(Signed)

a) Jeffrey L. Derevensky

b) S. A. Nemiroff

c) Helene Perrault

Date: Nov 3, 1992

Associate Dean (Academic)