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ABSTRACT

Modeling in all its forms (two-dimensional, three-dimensional, mathematical, and computer) is an essential feature of designing and making. This paper describes how 10 untutored technology education students in grade 7 used three-dimensional modeling while designing and making a solution to a technological problem. This paper is part of a larger study that explored the conflict between the design strategies students bring to the classroom and those advocated in the technology education literature. Subjects were paired into five single-sex dyads. Each dyad was given a design task to create a paper tower, with specific constraints and criteria for the finished product. Each problem-solving session was audio and video recorded. A retrospective interview was also conducted with the subjects. Subjects' comments during the problem-solving session and the retrospective interviews were transcribed, segmented, and coded into six categories. The first five coding categories describe the stages of the theoretical model of the design process: understanding the problem; generating possible solutions; modeling a possible solution; building a solution; and evaluation. The sixth category describes such activities as off-task talk and researcher instructions. Subjects used three-dimensional modeling to support a range of activities, including 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. (Contains 42 references.) (Author/SWC)

Students' Use of Three-Dimensional Modelling While Designing and Making a Solution to a Technological Problem[1]

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Introduction

The purpose of this paper is to describe how untutored technology education students use three-dimensional modelling while designing and making a solution to a technological problem. The paper is part of a larger study (Welch, 1996) that explored the conflict between the design strategies students bring to the classroom and those advocated in the technology education literature.

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. Designing (and its attendant making) is now recognized to lie at the heart of technology education. 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). As D. Barlex (1995) wrote "students [must be given] the opportunity to design what they can

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[1] Paper presented at the annual conference of the American Educational Research Association, Chicago, 1997. The paper is based on the doctoral dissertation entitled "The Strategies Used by Ten Grade 7 Students, Working in Single-Sex Dyads, to Solve a Technological Problem" (Welch, 1996). The author would welcome suggestions and comments based on this paper. Address: Queen's University, Faculty of Education, Kingston, Ontario, Canada, K7L 3N6. Tel: 613-545-6262. Email: Welchm@Educ.Queensu.ca

make and make what they have designed" (p. 1). 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?

Untutored students appear to have tacit knowledge of how to design and make a technological solution (Johnsey, 1995, Outterside, 1993; Welch, 1996). This knowledge derives from their experience of designing using materials, which 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 (Breckon, 1995). The ingenuity of childrens' sand castles, tree houses and skate board ramps are all examples of designing and making in action. It is reasonable to suppose, therefore, that by the time students enter secondary school they have a very significant fund of tacit knowledge about designing. However, the way in which students model their ideas does not conform to those advocated by textbook descriptions.

This paper will report aspects of a study that had as one of its aims the investigation of students' use of three-dimensional modelling. Following a review of the related literature, the methodology developed to elicit, capture and analyze the strategies used by subjects is described. This is followed by discussion of the way in which the modelling strategies used by subjects differ from those in theoretical models of the design process. The implications of these findings for the teaching of designing and making complete the paper.

Modelling as a Design Process Skill

Most technology education curricula and textbooks provide a "map" of the design process, typically comprising 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). Modelling in all its forms (two-dimensional, three-dimensional, symbolic, and computer) is an essential feature of the process (Murray, 1992; Smith, 1993). Ideas conceived in the mind need to be expressed in concrete form before they can be examined to see how useful they are. As Kimbell, Stables, Wheeler, Wosniak, and Kelly (1991) wrote, "it is [the] inter-relationship between modelling ideas in the mind, and modelling ideas in reality [that] is the cornerstone of capability in ... technology education" (p. 21).

Models are used by many people in many ways: a child uses a model farmyard as part of their play; an automobile designer uses a full-size model of a car in a wind tunnel test; a family uses a road map (a model of a geographic area) to plan a holiday; an architect uses a floor plan to make decisions about the location of doors and windows in a new house design. Clearly the term “model” has a wide range of meanings, yet in each of the examples provided above the model represents “a simplified representation of something created for a particular purpose” (Harrison, 1992, p. 32).

Types of Modelling

While the term "model" when used as a noun has a number of meanings, in the context of technology education the active form "modelling" is more commonly used. The term modelling includes modelling inside the head, that is, cognitive modelling or imaging, and modelling outside the head, that is, concrete modelling (Kimbell, Stables, Wheeler, Wosniak & Kelly, 1991; Murray, 1992). According to Murray (1992):

> Modelling inside the head includes the activities of imaging thoughts and ideas and shaping and forming those ideas using images and representational forms. These representational forms might be mental pictures: in stills, in series or moving; in the spoken or written word; or using other forms of language such as number or symbols. (p. 37)

Concrete modelling allows students to bring their ideas into the "real world" where they may be further developed, clarified, evaluated and communicated to others. Four types of concrete modelling are generally available to technology education students: two–dimensional, three–dimensional, symbolic, and computer (Barlex, 1994; Evans, 1992; Harrison, 1992; Sparkes, 1993). Two–dimensional modelling involves making representations of design ideas on paper. Techniques include rough sketches as the designer explores ideas, annotated diagrams, exploded diagrams, renderings to show finished form, and engineering drawings which permit making by someone else (Barlex, 1994; Johnsey, 1995). Three–dimensional modelling involves the use of construction techniques leading to "the fabrication of a form occupying space" (Harrison, 1992, p. 33). Resources may include easily worked materials such as paper, card, foam core, straws and coffee stirrers. Kits such as Lego, Meccano or Fischer Technic can be used to explore mechanisms and structures. Symbolic modelling uses a symbol to represent an object. For example mathematical formulae, calculations and graphs may be used to calculate bending moments in structures, to plot the loci of elements in a mechanism, or to plot load versus extension when testing materials. Another form of symbolic modelling uses standard symbols to represent objects; for example, symbols to represent components in a circuit diagram. Computer modelling may be used to explore the form of an object (3D modellers), to animate a mechanism (animation programmes), to explore a variety of finishes (paint programmes) and, using CAD software, generate working drawings (Barlex, 1994). Computer modelling may also be used to apply mathematical functions to data arranged in a spreadsheet, which can, in turn, be used to model economic and technical aspects of a technology (Harrison, 1992).

The Purposes of Modelling

In technology education, one can identify two contexts in which to discuss the purpose of modelling: that of the student and that of the teacher.

For the student, modelling may serve a wide range of purposes that includes visualising the whole or component parts of the product and its finished appearance, identifying possible faults in a design, framing ideas, testing the performance of a mechanism or circuit, testing ergonomics, examining the relationship of components, improving the form of the product, identifying the properties and working constraints of materials, communicating ideas and information to others, and evaluating their ideas (Davies, 1996; Evans & Wormald, 1993; Liddament, 1993; Sparkes, 1993).

For the teacher modelling serves a quite different purpose. Murray (1992) suggests that teachers should use a student's "modelling ... [as] evidence of the conceptual modelling that the student has engaged in" (p.39). But as Barlex (1994) warns:

> It is all too easy to see the end result of the modelling activity, 'the models', as the most significant part of the activity. They are only significant to the extent that they help the designer, be they pupil or professional, develop a clearer picture of that which she/he is designing and that, in the case of education, they reveal to the teacher the mental processes of the pupil in coming to grips with the design task .... It is important for the teacher to see them for what they are in educational terms – insights into pupil thinking. (p.79)

The danger for teachers is that when they perceive that the models are the most significant part of the design experience, then modelling may become a series of steps that students must take in order to provide evidence for teachers (Murray, 1992).

Given that modelling is a process skill essential to students' success when designing and making, how can it best be taught? What specific skills and knowledge are required? What materials should be provided? How do teachers help students express ideas? Because of its relatively recent introduction into the school curriculum, technology education has but a limited corpus of empirically derived research findings to answer such questions. The next section of this paper describes a methodology developed to investigate the modelling strategies used by untutored designers. For as Ausubel, Novak and Hanesian (1978) wrote: "the most important single factor influencing learning is what the learner already knows. Ascertain this and teach him [sic] accordingly" (p. 163).

Methodology

Ten Grade 7 students (six boys and four girls) were chosen from a pool of volunteers using the following criteria: (a) they should be articulate, (b) they should be able to work cooperatively, and (c) they should have maintained average to above average performance in school work. These criteria were 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.

Subjects were paired into five single-sex dyads. This partially reflects the real world of technology, in which most development occurs as the result of the efforts of two or more people working cooperatively. 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).

The Design Brief

Each dyad was provided with a copy of the following design brief:

> 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 task was selected for five reasons. First, the task 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, successful completion of the "Paper Tower" task requires engagement in the following design process steps; understanding the problem, generating possible solutions, modelling a solution, building a solution, and evaluating a solution. 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.

Each problem-solving session was audio and video recorded by the researcher. Subjects were encouraged to talk normally during the session. Within three days each dyad returned for a retrospective interview. Subjects watched the video of their problem-solving session. A video camera was positioned so that both the screen and the students could be video taped, enabling the researcher to document the segment of the task referred to by the subjects. The researcher started, stopped, or rewound the tape as subjects engaged in a semi-structured interview.

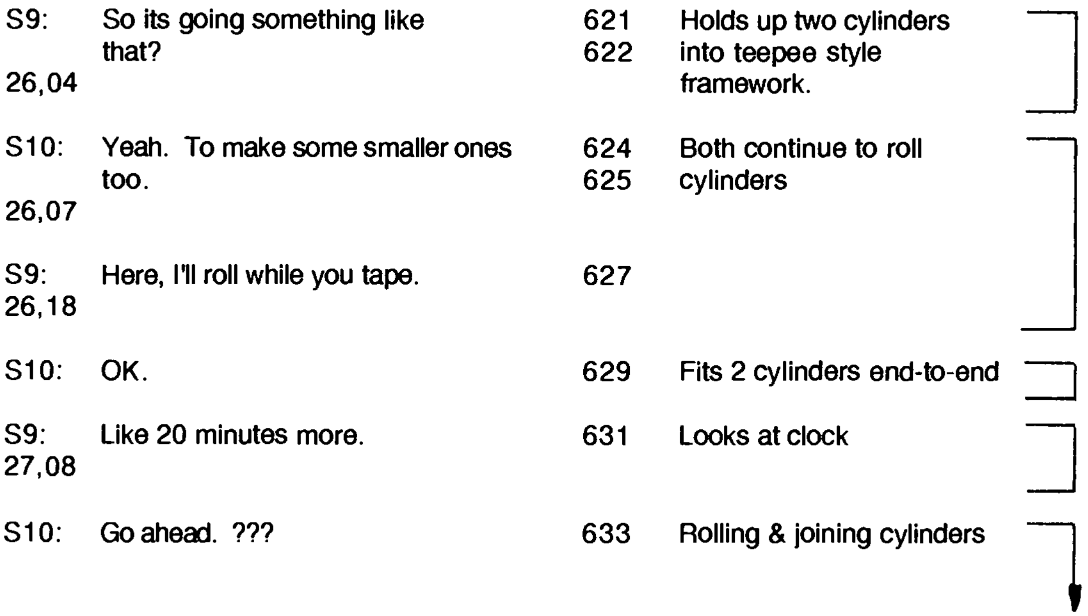
Following Hayes, Flower, Schriver, Stratman, and Carey (1985) concise, clear and consistent instructions were developed to ensure that all sessions were as uniform as possible. The instructions for the problem-solving session were in three parts. Part 1 consisted of a warm-up activity. Ericsson and Simon (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. 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 reemphasized. Subjects were reminded that they should talk normally and naturally during the session. 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 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.

Preparing the Data for Analysis

Analysis involved transcribing and segmenting subjects talk during both the problem-solving session and the retrospective interviews. Segmenting 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. 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 1 shows a sample of a segmented protocol.



S9: 26,04	So its 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 1. Sample of a segmented protocol

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; Newell & Simon, 1972; 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 the problem-solving task, and responses made during a semi-structured interview were used to inform this coding of actions.

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. Identical stages in the process were aligned horizontally. From this review a generic "sequence of actions" (Steps) and a start list of codes were developed.

A second approach to the derivation of a code set was then adopted and used to modify and extend the start list. 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. The coding scheme for this study contains six categories. The first five, requiring 24 discrete codes, describe the five stages of the theoretical model of the design process: (1) understanding the problem; (2) generating possible solutions; (3) modelling a possible solution; (4) building a solution; (5) evaluation. The sixth category includes eight miscellaneous codes, used to describe such activities as off-task talk and researcher instructions.

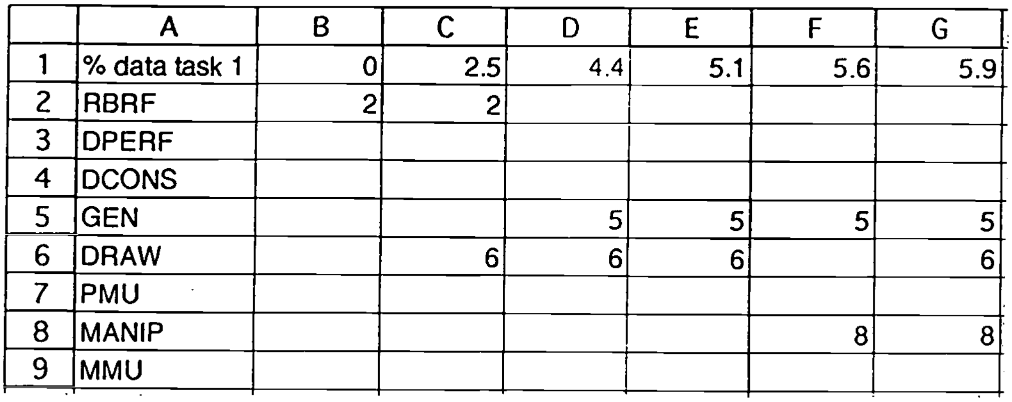
Mapping the Data

Models of the design process described in the technology education literature are frequently depicted as a graphic model, often linear and 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.

The data were entered into a spreadsheet program, 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. 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 2 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). 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 2. Data entry format

The final step in the analysis of data required the production of a series of empirical maps depicting the design process used by each of the dyads, and then the comparison of these to the theoretical design process.

The development of a theoretical map required reference to the technology education literature, in which the design process is depicted 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. However, to ensure that all subjects found a solution to the same problem, thus allowing a valid comparison of their sequence of actions, they 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 3.

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 3 the time spent on each step reflects a subjective interpretation based on a distribution implicit in a number of theoretical models. 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.

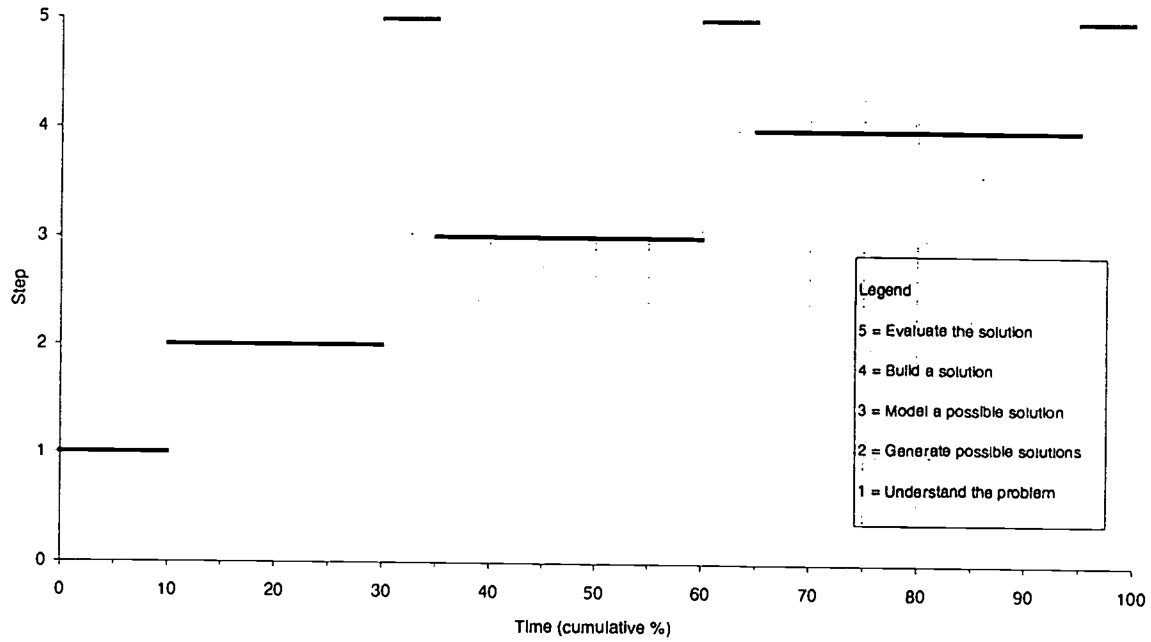


Figure 3. Map of the five-step theoretical design process used in this study

Results

According to the technology education literature, subjects, having generated a possible solution through discussion and drawing, should engage in three-dimensional modelling to explore the feasibility and efficacy of their proposed solution prior to making a prototype. Planning the making of a model (PMU), manipulating materials to explore elements of a possible solution (MANIP), making a model (MMU), and refining a model (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. Table 1 shows the time spent by subjects on each of these actions.

Table 1

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*

Analysis of the data made evident five significant differences between the role of modelling as described in design process models and the untutored strategies of subjects (Figure 4 is representative of the map generated for each dyad).

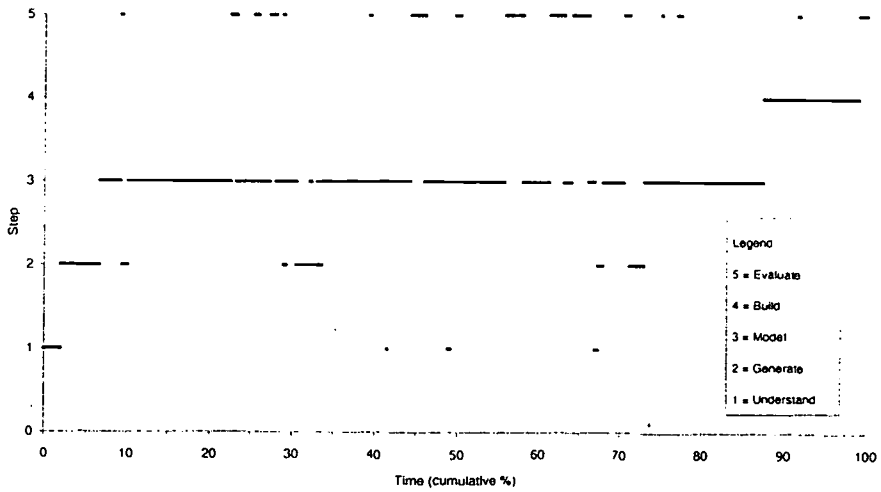


Figure 4. The strategy used by Dyad 5

First, subjects used three-dimensional modelling to largely replace two-dimensional modelling, that is, sketching. In textbook models of the design process, students are expected to sketch several possible solutions prior to selecting and 3-D modelling the one which they judge to offer the most promise as an effective solution. In this study subjects spent, on average, only 8.5% of their time sketching. In all five dyads, generating possible solutions was accomplished not by sketching but by modelling with three-dimensional materials. Indeed, the low importance given to sketching is emphasized by the actions of several subjects who, having made minor attempts at exploring their ideas on paper, promptly used the same piece of paper to model a solution. As one subject said "I started fooling around with the paper and I completely forgot about the drawing". In other words, subjects did not use 3-D modelling to further develop some "less-developed form", but rather to "originate [and] develop ... their ideas" (Evans & Wormald, 1993, p. 97).

Second, this study showed that subjects did not present several solutions at the outset. They were more likely to develop solutions serially: an idea was 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, was similarly developed. Third, subjects used three-dimensional modelling to fuel ideas for further cognitive modelling, which then needed to be tried out in concrete form. When Dyad 4 had 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 said "Okay, um, we could cut it [a sheet of paper] in three". It appears that simultaneously generating ideas and modelling with three-dimensional materials was an important aid to subjects' thinking about a solution. Fourth, modelling was used not only to develop but also 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". S2 then proceeded to cut and bend four tabs at the bottom edge of the tower in order to form a base. Fifth, analysis showed that subjects were repeatedly and constantly evaluating their models from the first moment that making began. Testing during modelling often led to the identification of a design problem and suggested refinements. The data also suggest that evaluating led to the acquisition of knowledge which subsequently informed the design of the next solution.

Discussion

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, three-dimensional modelling is intended to externalize ideas. 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 increase understanding of the problem; to externalize a cognitive model; to transform a two-dimensional model, that is, a sketch, into a three-dimensional form; to fuel ideas for further cognitive modelling, which then needed to be tried out in concrete form; and to test or evaluate 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 the pre-study observations of the researcher, by developmental theory, or by the results of this study. Rather, the results suggest that it may be 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 prior to planning and exploring ideas using 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, that is, with two-dimensional models, before moving to the task environment working with three-dimensional models. 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.

Table 1 showed that subjects spent, on average, less than one percent of their time planning prior to making a model. 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 (1995) 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). 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.

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 suggests that subjects did not have the skills or knowledge to enable predictive designing to take place. But 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 (1995) 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 data also suggest that seeing an idea translated into a three-dimensional model stimulates additional idea generation. For example, Subjects 9 and 10 (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,
> you know how they build big castles out
> of cards? (lines 854-856)

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
> that like that and then put a base
> around it, put the base to it and
> added little pieces of paper at the
> top. Watch, I'll show you.
> S9: You need a base around the bottom
> if you're going to put all that weight
> at the top. (lines 863-871)

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 (Subjects 7 and 8) 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).

Conclusion

This study has illustrated the role of modelling using three-dimensional materials as untutored technology education students design and make a solution to a problem. Modelling was used to support a range of activities, including 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 Schön (1987) has written "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). What remains to be explored are such questions as: What are the most appropriate skills to teach students in order to facilitate their ability to externalize ideas? At what stage in their development as designers can and should students be taught two- and three-dimensional modelling skills? How are these skills best taught? Which materials best support students' learning of modelling techniques? And, perhaps most importantly, what cognitive development occurs as a result of a student's engagement in the design process skill modelling?

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