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Sixth form students' ability to engage in computational modelling

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Abstract The paper presents the main conclusions of an exploratory study of the ability of Sixth form students in England to use some different approaches to computational modelling. The research involves a questionnaire survey of causal diagraming and mathematical knowledge, which aims at characterizing students' model building capability. Also, it includes an intensive study with pairs of students doing exploratory and expressive tasks using two modelling systems: *IQON* and *STELLA*. Data was gathered through written notes from observation, written answers given to questionnaires and data recorded in the computer. Overlapping questionnaires connected the survey and the intensive study, and comparisons between the use of causal diagrams and *IQON* were carried out. Results suggest that Sixth form students can undertake valuable work with both computational systems.

Keywords: Causal-loop diagram; *IQON*; Modelling; *STELLA*.

Introduction: modelling and modelling systems

With modelling now prominent in schools (National Curriculum Council, 1990), the efforts made over the past decade to develop computer systems to help teachers and pupils build computer models now have to be converted into curriculum practice. This research gives an account of Sixth form students' ability to manage some different approaches to modelling; namely causal diagrams and a pair of computational tools: *IQON* and *STELLA*.

Kinds of computational tools

Bliss and Ogborn (1989) present a classification of kinds of tools into quantitative, semi-quantitative and qualitative. By quantitative tools they mean modelling systems such as DMS (Ogborn & Wong, 1984; Wong, 1986), CMS (Holland, 1988), *STELLA* (Richmond *et al.*, 1987) and spreadsheets. By semi-quantitative tools they mean tools which would support reasoning involving relations between variables such as 'larger than' or 'smaller than' and effects

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of one variable on another such as 'X increases Y' or 'X decreases Y', without necessarily involving specific mathematical relations (see Forbus, 1982; 1985). They pointed to the necessity of developing a semi-quantitative tool, which later took shape as the tool *IQON* (Miller *et al.*, 1990). The research described here concerns the use of the semi-quantitative modelling tool *IQON* and the quantitative modelling system *STELLA*.

Exploratory and expressive learning modes

It has been proposed (Bliss & Ogborn, 1989; Bliss *et al.*, 1992) that there are two different but complementary ways of using a computer tool — the exploratory and expressive learning modes. In the exploratory mode, the students explore a model already in the computer, thus exploring representations, developed by a teacher or researcher, which may be different from their own. In the expressive mode, the students develop their own models, which are their own representations of the 'reality' being modelled.

Causal loop diagrams and system thinking

Causal loop diagrams are directed graphs in which nodes represent variables and arcs represent influences of one variable on another. Causal loop diagrams can provide insight into a system's structure, but it is often difficult to infer the behaviour of a system from its causal loop representation. It is necessary to move from a causal loop representation to a computer simulation model, traditionally first developing a flow diagram, as recommended for the system *STELLA*. A key element is a search to identify closed, causal feedback loops (Kurtz dos Santos & Ogborn, 1992). The emphasis on causal loops can be a powerful tool to help define a system's boundary, and to sort out what should and what should not be included within the study of a social, economic or other system.

STELLA

A quantitative modelling tool, *STELLA*, (Structural Thinking Experimental Learning Laboratory with Animation) has been developed for the Apple Macintosh computer (Richmond *et al.*, 1987). It uses a metaphor of pipes, valves and tanks (see *STELLA* diagrams below). In *STELLA* a tank (stock, level) represents a quantity which can increase or decrease from some starting value. A tap (rate) connected to a tank decides how quickly the amount in the tank is changing. Quantities represented by other convertors can be constants, or can be calculated from other quantities.

STELLA makes the construction of a model possible through the diagrammatic linking of these basic objects as in a causal diagram, and the structure of the diagram automatically determines that of the model. Algebraic relations between variables have to be written, but the system itself converts them into program code. *STELLA* allows a graph to be plotted of any variable against any other, and generates tables of output data.

Animating causal diagrams — IQON

The ESRC Tools for Exploratory Learning project (Bliss & Ogborn, 1989) developed a semi-quantitative tool, *IQON*. Ogborn (1990) describes the idea of building models by linking modules representing changing quantities without saying anything about their absolute values. Such a model is built by linking together identical modules, with links transmitting positive or negative influences from the output of one module to the input of another. At each iteration the inputs to each module are added to its current value.

Figure 1 shows a model for the Greenhouse Effect in *IQON*. Amongst the boxes that represent the main variables, 'Energy radiated', for example, is the amount of energy radiated or reflected back into space from earth. 'Land clearance' is the amount of land cleared for building and agriculture and 'Sun's radiation' is the amount of energy reaching the Earth from the Sun.

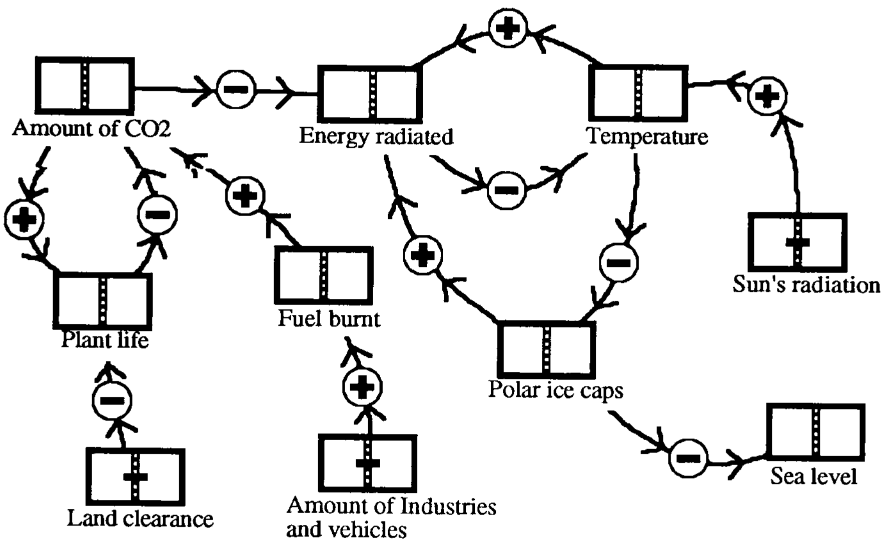

Fig. 1. *IQON* model for the Greenhouse Effect.

Structure of the research

General research questions

The present research is about students' ability to manage different approaches to modelling. Consequently, the first general question is:

> *Can sixth form students achieve success or some valuable work with (certain) computational modelling systems?*

This general question can be split into three general sub-questions:

- *What is required for students to use or make computational models?*
- *How good are (certain) modelling systems as tools for making models?*
- *How is students' thinking with models related to their other knowledge?*

The second general research question, related to modelling is:

> *What can be said about the model building capability of sixth form students, without using the computer?*

Choices of tools and types of task

In order to approach these general questions it was decided:

- to work with both semi-quantitative and quantitative tools;
- to involve causal diagrams because:
  - the literature about *STELLA* claims they are important,
  - they make possible the link to quantitative models,
  - they offer a possibility of comparison with *IQON* models;
- to work intensively with a small number of students because modelling tasks take a lot of time;
- to complement the intensive study with a larger scale survey about abilities and knowledge needed for modelling.

Research design and instruments

Figure 2 gives an outline of the research design (see Kurtz dos Santos, 1992 for more detail).

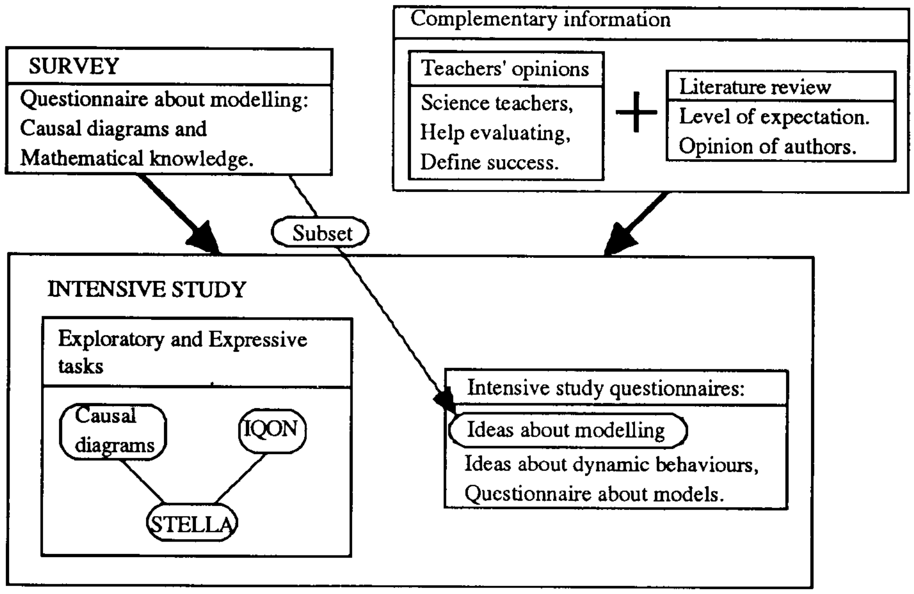

Fig. 2. Schematic research design.

The survey questionnaire, including items about causal diagrams and mathematical knowledge, was used as background for the small scale intensive study, which included a questionnaire having some items in common with the survey. The survey questionnaire contained one part about variables and the drawing of causal diagrams, for example:

> The Greenhouse Effect
> CO_2 in the atmosphere 'traps' sunlight, and warms the Earth. CO_2 is added to by burning fuels. CO_2 is removed by vegetation. The Earth's temperature is reduced by reflection from polar ice, but a high temperature can melt polar ice. Ice melting raises sea levels . . .
> Make a diagram which explains this situation.

The second part of the questionnaire is about the relevant mathematical knowledge needed to engage in modelling, including questions about simple algebraic relationships, interpretation and construction of graphs, meanings of simple expressions including time derivatives, and interpreting short sections of computer code (e.g. iterative incrementing loops). The questionnaire also included questions about students' previous use of software and hardware.

In the intensive study, half the sample worked first with *IQON* and half with causal diagrams, on parallel exploratory and expressive tasks. Both groups then went on to work on exploratory and expressive tasks with *STELLA*. Thus *IQON* could be compared with causal diagrams, both on parallel kinds of task and as a preparation for work with *STELLA*.

In addition, opinions of science teachers were collected about the difficulty of tasks given in the intensive study, and about the merits of sample explanations and models produced by students, to help serve as a bench mark to evaluate students' performance in the intensive tasks. A literature review further helped define expectations about what students could do with modelling systems.

Students in the intensive study were also asked to select graphs representing the possible dynamic behaviour of a number of different examples (e.g. a growing population). Further questions investigating their conceptions of models were given both before and after their work with modelling tools. Figure 3 gives some examples of these questions.

	agree	partly agree	partly disagree	disagree
1) If the model predicts things wrongly it must be wrong.	☐	☐	☐	☐
5) Only a very small part of reality can be understood through models.	☐	☐	☐	☐
9) A model should try to reproduce reality in all its complexity	☐	☐	☐	☐

Fig. 3. Examples of questions — questionnaire about models

In the intensive study, students were given detailed printed tasks, and worked in pairs. An observation schedule was used, together with notebook records and data collected by the computer, to record data as the students worked on the tasks, in which they provided further data in the form of written answers.

Samples

Survey sample

Both parts of the survey questionnaire were completed by a total of 67 sixth form students, in four London and two Kent schools (45 London students and 22 Kent students). The average age of the students was 17 years, and all were taking at least Physics A-Level. All the schools offer regular A - Level courses in many subjects.

Intensive study sample

Table 1 shows the distribution of students in the intensive study by main A-level subject background, age and gender. Random selection was impossible, and students were selected according to their willingness to participate in the experiment. In consequence it was impossible to avoid this undesirably uneven distribution of age, gender and background.

Table 1: Distribution of students in intensive study by background, gender and age.

Background	gender	age	number	totals
Physics	male	16-17	6	
		17	2	
	female	16-17	0	
		17	4	12
Economics	male	16-17	4	
		17+	10	
	female	16-17	2	
		17+	6	22
			TOTAL	34

Intensive study modelling tasks

Figure 4 shows in more detail the structure of the intensive modelling tasks, including parallel *IQON* and causal diagram tasks done by different groups, followed by tasks with *STELLA* done by all students. All students had first to learn to use the Macintosh computer, including the use of the mouse and of menus, to prepare for later work with *STELLA*. This was done for the group who worked with causal diagrams by using MacDraw to draw these diagrams, and for the group which used *IQON* in the course of learning to use *IQON*.

The model for the Greenhouse Effect used in the exploratory task with *IQON* is shown in Fig. 1 above. The same causal diagram was presented on paper to students who just used causal diagrams. Both groups were asked to explain the effect of making different variables high or low, the group using *IQON* being asked to try it. An example of an answer from a student in the *IQON* group asked to explain what happens to the temperature when the variable 'amount of industry and vehicles' is made high is:

"It goes up. Industry and vehicles increase, so amount of fuel burnt must increase. An increase in burnt fuel means and increase in CO_2. More CO_2 means less radiation energy deflected off the earth..., as it cannot so easily penetrate CO_2. If less energy is radiated, when the form of energy is heat, then if it is trapped the temperature must rise". (Student)

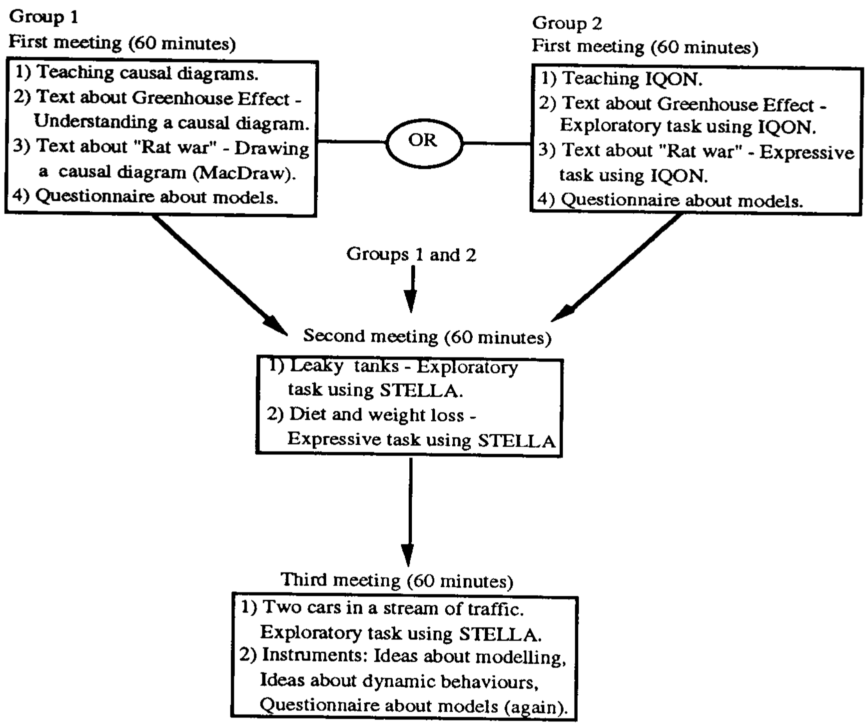

Fig. 4. Structure of tasks of intensive study.

For the expressive task, after reading a text about the explosion of the rat population in London, students were asked to model the situation by themselves, using *MacDraw* to make causal diagrams or using *IQON*. Figure 5 shows an example of an *IQON* model, including two feedback loops, developed by one pair of students.

The initial exploratory tasks with *STELLA* were designed to be based on a physical situation about which students should have intuitive ideas, which they might have worked on formally in Science courses, and which fits closely with the *STELLA* metaphor: 'leaky tanks'. The first task (Figure 6) was to explore a model of a situation where one tank leaks into a second tank which also leaks.

Equations for the model were given. The students were asked to run the model and to answer questions such as, "What happens to the level of the second tank? Why?"

An explanation given by one student recognising the simultaneous action of two rates was:

'dh1/dt of first tank is, initially, high compared to dh2/dt and so h2 rises. After a certain time dh1/dt decreases and dh2/dt increases until they are equal, the maximum h2. After this dh2/dt is greater than dh1/dt and so level of h2 slowly decreases'.

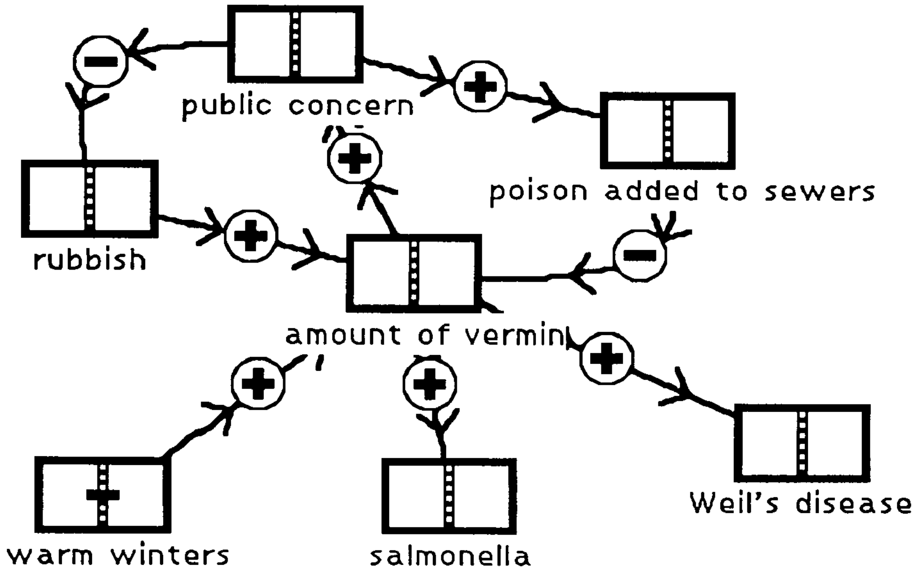

Fig. 5. Students' *IQON* model for the expressive task 'Rat War'.

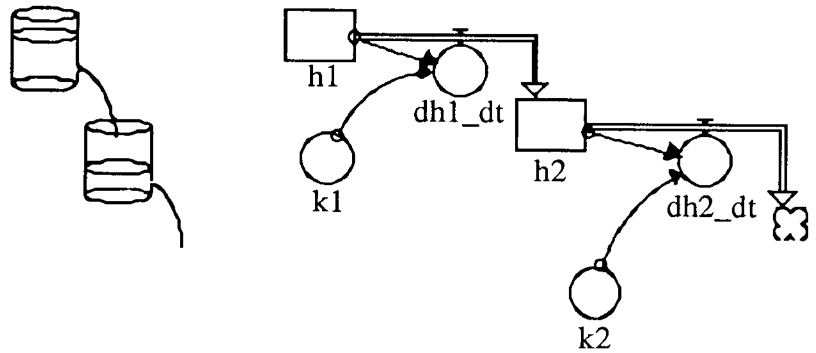

Fig. 6. Two leaky tanks, and the model in *STELLA* .

For the expressive task with *STELLA*, the starting point was the following:

> If you regularly take in more calories in food than you lose in moving about and in heat losses, then you grow fatter and heavier. But the heavier you are, the more effort you need to move around, so you do not go on for ever getting fatter, but stop at a heavier weight.

Students were asked to make a diagram in *STELLA* of a model which could be used to experiment with the effects on body-weight of over-eating or of dieting. They were not asked to add the necessary equations to make the model runnable, but were asked how it would work.

In the third and last session, students were given a *STELLA* model for the interactions of speeds of two cars, one following the other (Figure 7), as an exploratory task. They could run the model, observing the changes in variables, and asking for graphs of any variable as a function of time. The model was constructed so that the distance between the cars grew or shrank according as there was a difference in their speeds. The acceleration or deceleration of the following car depended on the distance between the cars. The equations used in the model were given.

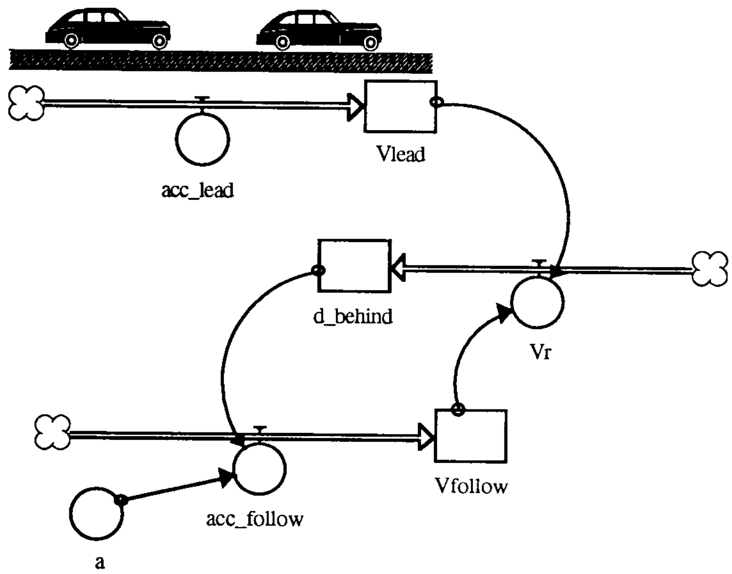

Fig.7. *STELLA* model for exploratory task 'Two cars in a stream of traffic'.

In this model, oscillations of the distance between the cars are possible. Students were asked what happens when the model is run, whether this could happen in reality, why the model in the computer behaves as it does, and could they think of any other situation which behaves in the same way.

Networks for data analysis

An important part of the data concerned students' construction of causal diagrams and *IQON* models, and their accounts of them. A systemic network, shown in Fig. 8, was used to define features needed to describe the variables and links which students used.

The network in Fig. 8 describes aspects of students' answers on four dimensions:

- the nature of the entities invoked;
- the nature and status of the links used;
- the structure of the causal diagram;
- the mechanisms used to explain the system.

Entities are the things used as nodes in a causal diagram. Some of them are variables, which the network distinguishes:

- quantifiable: an amount or level (e.g. weight or height);
- quantifiable: a rate or change (e.g. loss of weight, interest rate);
- non-quantifiable: an amount or level (e.g. fitness, awareness);
- non-quantifiable: a rate or change (e.g less leisure, greater fitness).

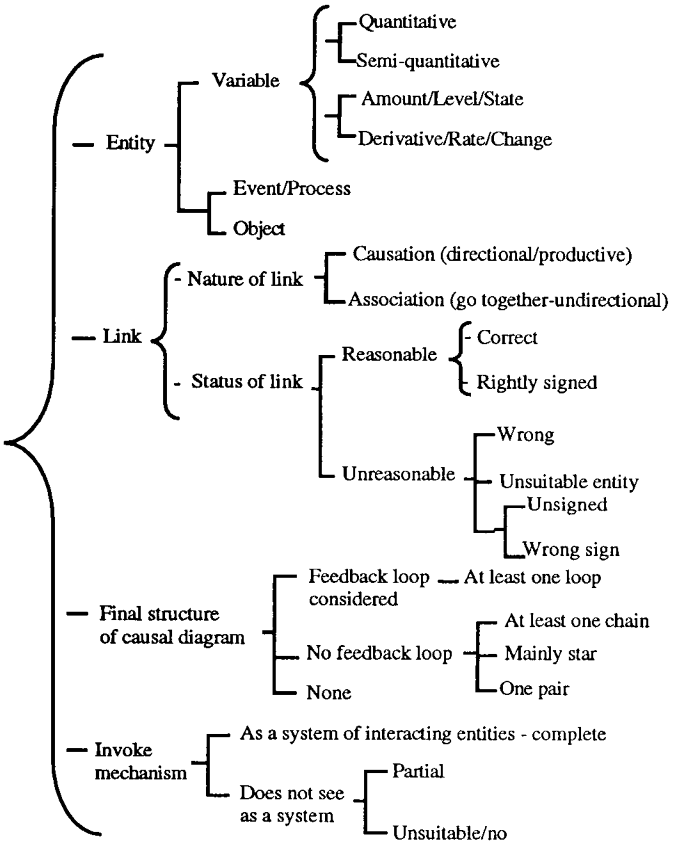

Fig. 8. Network for analysing data on nature of models constructed*.

Other entities used by students are not variables. A *process*, following Forbus (1985), is an action of some kind, for example, 'eating'. A process can be more or less intense or active. Other examples are burning fuel and reproduction. An *event* is something localised in time that just happens, for example, starting or stopping eating. It does not relate to any sort of quantity. Examples of events are, a car moves away, foxes die, rabbits survive. We have an *object* when the 'variable' is seen as a thing or a person. Examples of objects are a car, or the Earth.

* Figures 8 and 9 follow the conventions in Bliss, Monk and Ogborn (1983). Selections are made from all systems following a bracket. One selection is made from a system following a vertical bar.

Links between entities were described both in terms of their nature and their reasonableness. Following Bunge (1963) links are described as involving causation or just association (simply going together). A link was described as reasonable if it indicates a correct causation or association between two entities and is correctly signed. A link was described as unreasonable if it indicates a false causation or association between two entities, has the wrong sign, or links together a pair of entities one or more of which is unsuitable.

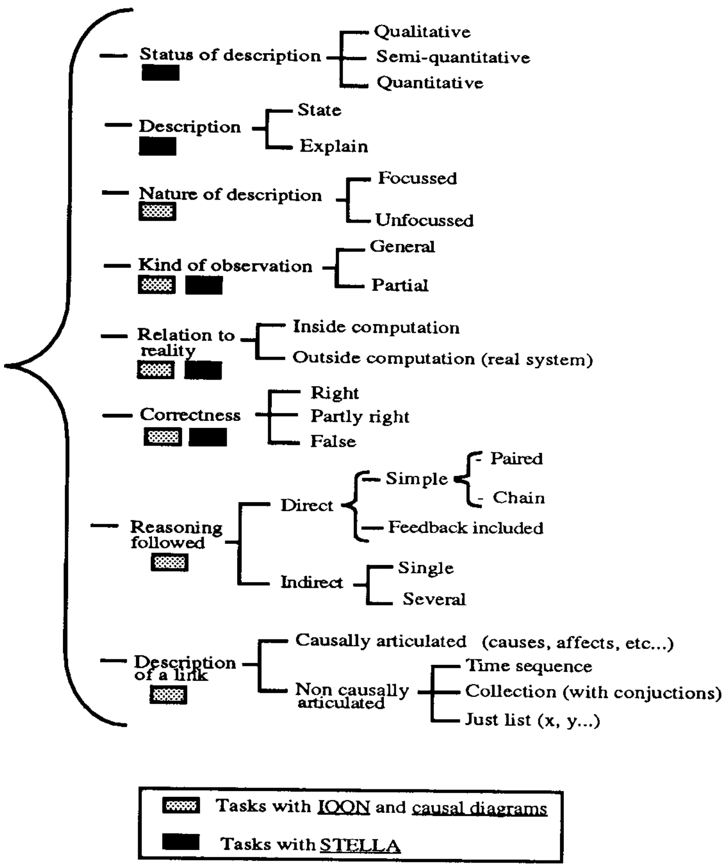

Fig 9. Additional network for analysing data in the intensive study.

Besides describing individual nodes and links, it was important to describe the whole structure of the diagram or model. The structures were divided into those which contained *at least one feedback loop* and those which did not. Those which had no loops could consist, in decreasing order of complexity, of chains of several linked entities, of a star-like structure where several entities all affected just one other entity, and at the simplest, a single pair of entities.

The network in Fig. 9 adds dimensions to those of the network described in Fig. 8, to help the two together to describe the ways students in the intensive study reason about models, using both *IQON* and *STELLA*.

Explanations given by students were analysed as qualitative, semi-quantitative and quantitative, and as to whether the account given by the student was explanatory or descriptive. Their accounts were described as focussed if the explanation concentrated on entities relevant to the behaviour being explained. The kind of observation of a model was described as general if the student saw a general pattern of behaviour, or as partial or localized if the account merely reported what happened to a certain number of entities in the model.

A student was described as thinking outside the computation when thinking about entities which are related to the real physical system, but which are not explicitly represented in the model. An explanation is counted as right if it gives the correct account for the expected behaviour of a dependent variable. It is counted false if the student makes the wrong prediction of what happens to the main dependent variable. An explanation can of course also be partly right.

The reasoning followed was considered direct when it described a chain or pair of entities, or feedback. Indirect reasoning just described what happened to isolated entities in the model. The description of a link was considered causally articulated when linguistic indicators like *causes, affects, will lead to,* were used, or as non-causally articulated when it was described in terms of a time sequence, a collection with conjunctions or just as a list.

All the definitions of features given above were arrived at by an iterative process, classifying aspects of the data tentatively, building an initial network, reclassifying and modifying the network until two independent coders could agree on at least 80% of codings. Remaining minor disagreements were resolved by discussion.

Summary of results

The results of the research necessarily have to be obtained by piecing together evidence from the different kinds of questions asked in the survey, and from the different activities in the intensive study. They are given here in summary form, as answers to the research questions posed above, together with examples of the evidence on which they are based. Full details can be found in Kurtz dos Santos (1992).

> *What can be said about the model building capability of sixth form students, concerning work with causal diagrams and the mathematical knowledge relevant to modelling?*

Eighty per cent of the students surveyed had some experience of using computers. The students showed a reasonable initial model building capability. Students surveyed could interpret and construct graphs (mean scores about 70%), and they could manage the simple algebraic relations needed for simple quantitative modelling (mean scores on questions ranging from 60% to 80%). They coped with iteration in simple cases (e.g. compound growth — mean score 80%). They were less good at understanding rates of change expressed using derivatives (mean scores ranging from 30% to 50%). They had difficulty with interpreting models expressed as difference equations in the form of simple BASIC code (mean scores 30-40%). Thus attention needs to be given to programming if quantitative modelling in a computer system is to be undertaken. They were too strongly inclined to interpret change as likely to be linear and increasing (for example a linear graph or one curving upwards were was nearly always the first choice for a graph to express any kind of change).

They could construct plausible models in the form of causal diagrams (90% of students surveyed attempted a model, for each of four problems given), or at least models which teachers generally judged to be acceptable or interesting. These diagrams were rarely complete models, but generally contained relevant entities and links, and provide at least a good starting point for discussion and further work.

In using a computational modelling system the conceptualisation of entities as variables is fundamental, but can not be taken for granted as natural for all students. For some situations students will tend spontaneously to use events, processes or objects instead of variables. The extent to which they did so depended rather strongly on the nature of the problem. Variables were most often used in physics-related problems by students with a physics background. They were least often used, by all students, in a general problem about the Greenhouse effect, where objects and events figured largely. Thus the analysis of systems in terms of variables, which seems obvious to the expert, is not always obvious to the student, and will often require attention in teaching.

What is required for students to use or make computational models?

The following aspects seem important:

- reasoning in a semi-quantitative way;
- potential for the use of causal diagrams and *IQON*;
- imagining the world in terms of variables;
- knowledge about rates of change;
- thinking at a system level;
- understanding causation in a system.

Semi-quantitative reasoning

Semi-quantitative reasoning is natural even in quantitative tasks. For example, all students in the intensive study reasoned semi-quantitatively when explaining how a *STELLA* model worked, after they had seen it run. It is present when thinking about causally connected entities, and thus in developing or understanding causal diagrams. Semi-quantitative reasoning tends to be complex and seems to depend on subject matter (a factor analysis of responses to mathematical questions in the survey gave, besides a 'mathematical ability' factor, another factor which seems to represent semi-quantitative reasoning, which was however more strongly associated with some causal diagram problems than with others). Students reasoned semi-quantitatively and satisfactorily when working with modelling tasks, in terms of entities, structures and output (about 70% of choices of graphs to represent changes expressed semi-quantitatively were correct; only five out of eighteen semi-quantitative models designed with *STELLA* in the intensive study were rated by teachers as poor; over half the entities included in causal diagrams in the survey were variables regarded semi-quantitatively). There was some indication that semi-quantitative reasoning might depend on gender and background: female students, and students with a background in Physics, were responsible for larger fractions of semi-quantitative descriptions of *IQON* and *STELLA* models, and achieved better in system thinking tasks.

Causal diagrams and IQON

Students who worked only with causal diagrams and not with *IQON* in the intensive study had some difficulty with them. Given a causal diagram representing the Greenhouse effect, five out of nine pairs made wrong predictions about changes implied with the model, and most pairs had trouble understanding the meanings of links, particularly negative ones. Students who were given exactly the same model but in *IQON*, who could run the model, understood it much better and had less trouble with negative links. Students working only with causal diagrams quite often focused only on cause-effect pairs or described the behaviour of isolated entities (ten out of eighteen), while students working with *IQON* more often gave complex descriptions of model behaviour (twelve out of sixteen). Six out of eighteen students given a causal diagram said it was hard to understand; none of the sixteen given the same model in *IQON* said so.

In constructing their own models in the intensive study, students using *IQON* much more often used variables (rates or amounts) than did students just using causal diagrams (30 out of 53 links constructed using *IQON* were between variables; only 2 out of 70 links in causal diagrams were between variables). It seems that *IQON* was very helpful to them in this respect.

Criticisms of the model by those using *IQON* tended to be more sophisticated (over two thirds of criticisms given by those using causal diagrams complained simply either of the missing quantitative aspect or of the difficulty of understanding them; by contrast half the criticisms of those using *IQON* were more specific and pointed to particular limitations of the model).

Thus students who worked with *IQON* in general achieved better than those who used causal diagrams, both in exploratory and in expressive tasks. *IQON*, due to its runnability, seemed to help them to think about systems as a whole.

Despite *IQON* having provided a more malleable environment to develop causal diagrams, the work with *IQON* and causal diagrams did not however have any significant effect on achievement in expressive tasks with *STELLA*, comparing teachers' ratings of models constructed in *STELLA* by the two groups (students with a physics background did however do better than those without: F ratio 11.8, $p = 0.004$). If correct, this result raises practical questions such as whether it is worth investing money for *IQON* to run causal diagrams in a computer, when they can be drawn cheaply on paper. The decision will have to be based on other criteria, for example the value of introducing computer models.

The idea of a variable

The idea of a variable is critical for dynamic modelling. When modelling a dynamic system the student has to imagine the world in terms of variables. Students in some cases replace variables by objects, events and processes, though this seems to depend very much on the problem. In a physics-related question about flow of water from a tank in the survey, asked to cross out suggested 'variables' which were not relevant to the problem, students more than twice as often deleted non-variables (e.g. 'the water') as they deleted variables (e.g. 'water pressure'). But, in the survey questions asking for causal diagrams to be constructed, as many as half the 'variables' suggested by students could be objects or events, though this varied widely between problems. We noted above the tendency for the use of *IQON* to promote the use of variables.

Time does not normally appear as a causal variable in dynamic models, even though it is relevant because dynamic models evolve in time. In constructing causal diagrams for questions in the survey, only about 20% of students used time as an active causal agent, even though 'time' was listed as one of a number of possible relevant 'variables'. A very similar fraction of arguments about models used time in this way in the intensive study. It can be seen as a good feature that students tended not to use time as an active entity in causal diagrams.

The articulation of variables in explanations may indicate whether the student was able to imagine the world in terms of variables. Even when working with Physics related situations in the intensive study students tended not to use variables in their explanations of water flow between tanks whilst trying to construct a model in *STELLA*. Explanations were rich in objects such as 'the tank' and 'the water'. Variables were mostly used by students with a background in physics (all physics students used some variables in their explanations; 40% of explanations from non-physics students used no variables).

The idea of rate of change

The idea of rate of change is fundamental to quantitative modelling and to understanding models in *STELLA*. The idea that a variable changes seemed not to be a problem (as noted above, students could successfully interpret and construct graphs of changing quantities). The problem seemed to be the representation of the rate of change of a variable as itself another variable (for example, of students in the survey, asked to describe flow from a tank, only about 10% did so using any idea of a rate of flow as a variable; also we noted previously difficulties with derivatives).

System thinking

System level thinking presented students with some difficulty. One aspect of system thinking is the role of feedback. About 30% of students in the survey misinterpreted the behaviour of entities involved in feedback, in a question showing a clear feedback loop in a causal diagram. Also, asked to construct causal diagrams for which feedback loops were appropriate, the proportion of students who included them varied from about 30% to about 60%. The proportions were highest for complex non-technical problems and lowest for simple physics-related problems.

In the intensive study, it was in expressive tasks that students showed some ability to construct interconnected systems. More than half the pairs working with *IQON* did so, as compared with only two out of nine pairs working with causal diagrams.

Causal thinking

When deciding how to model a system in terms of variables, links and feedbacks, one has to account for 'what causes what' and 'how'. A student needs to be able to link entities reasonably in a model and to give mechanisms to explain the links. As others have done, we found a prevalence of 'linear' causal reasoning (one cause, one effect) over more complex thinking.

This does not mean that students do not understand causes. For causal diagram construction problems in the survey the proportion of reasonable links proposed could be from 50% to 90%. However, the causal reasoning of students in the intensive study when working with exploratory tasks was often unsatisfactory, though they did better in this respect in expressive tasks.

How good are IQON and STELLA as tools for making models?

Students can learn *IQON* very quickly. The teaching tasks seemed sufficient to put the students in a position to explore *IQON* models. The teaching and exploratory tasks may have helped students to express themselves with the tool. After being taught, students had few problems in dealing with *IQON*'s basic functions. Similarly, students could quickly learn to deal with the basic operations in *STELLA*, although a few of them asked for help.

STELLA's metaphor seems to have a strong influence on the way the student thinks about variables. Unlike work with causal diagrams and *IQON*, where the student is free to choose entities, *STELLA*'s structure works as a 'strait jacket', which obliges the student to use the idea of rates of change. When not confident of this idea, students cannot express themselves with the tool.

Because of *IQON*'s limitations, activities must be carefully chosen, since not any kind of system can be represented with the tool. *STELLA* is more powerful, but for this reason demands more extensive and specific previous instruction to be successfully used.

Recognition of structure

In the literature the identification of the underlying structure of a problem and the transfer of this understanding to other problem areas is seen as a key element of problem solving (Bruner, 1960).

For exploratory tasks, students were in fact able to suggest other related situations that could be modelled with the same *STELLA* structure. For example, over half suggested an economic analogue to a model of flow of water between tanks. Three quarters of the suggestions went well beyond simple similarity, for example suggesting a diet analogue of a model of two cars following each other along a road, and not merely changing it into (say) two people following one another. Since students were able to articulate analogies, the teaching of structures of models by the use of analogies as proposed in Kurtz dos Santos and Ogborn (1992) appears to be a possibility.

How do students understand 'modelling'?

Students in the intensive study twice answered a questionnaire about the nature of models, once after the first session and again after the last. Broadly, their opinions seem rather reasonable. Over half agree initially that only a small part of reality can be understood through models, with a few more shifting towards agreement afterwards. Two thirds agreed that models represent only very simplified aspects of reality. Nearly all opposed the notion that a model which is very simple can hardly be true and took this position even more strongly afterwards. Opinion was widely divided about whether a model should try to reproduce reality in all its complexity.

Two thirds saw that a correct model is not the same as the real thing, and more did so afterwards. All but two agreed that a model can be approximately correct, and more than two thirds did not agree that, 'all that matters about a model is whether it works, not whether it is correct'.

Less reasonable perhaps was the three quarters majority in favour of the statement, 'there must be a correct model of every situation even if we can't yet find it'. But almost as many took the perhaps sophisticated view that, 'pure guess-work with models can be helpful for thinking about a situation'. Overall, these responses suggest that further work on and thinking about models has a good basis from which to begin.

Judgment of models

For exploratory tasks with *IQON* and causal diagrams, students in general considered variables, links and correct structure as the main features in judging a model as accurate. The ability to offer reasonable criticisms of a model suggests that the student has reached a good level of understanding of the model and of what it represents. About half the students could reach such a reasonable level of criticism.

Can sixth form students achieve success or some valuable work with either or both modelling systems?

There is enough evidence throughout this research to say that students can do some valuable work with *IQON* and *STELLA*. Students showed some positive achievements in expressive and exploratory tasks with causal diagrams and modelling systems.

Recommendations

1. Use modelling tasks to help make explicit students' own ideas about a domain, and about modelling.
2. Use both exploratory and expressive tasks. Students can manage greater complexity in exploratory tasks, but achieve more system thinking, and a better level of criticism of models in expressive tasks.
3. Use both everyday situations and ones closely related to the subject matter to be taught. Modelling everyday situations can bring out deep problems about the nature of modelling.
4. Expect difficulties with defining situations in terms of systems of variables, and anticipate the introduction of processes, events and objects in their place.
5. Be prepared to have to introduce explicit teaching about the rate of change of a variable as itself a variable.
6. Respect the potential value of semi-quantitative thinking, in allowing complex systems to be considered without mathematical difficulties intruding.
7. Use either causal diagrams or a system such as *IQON* to represent systems. *IQON* has some advantages in being runnable and in helping to produce a better level of thinking.
8. If using *STELLA*, be prepared for a considerable time needed to learn how to use it.
9. Look for opportunities to show analogies between different systems, to encourage transfer.

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References

Bliss, J. Monk, M. & Ogborn, J. (1983) *Qualitative Data Analysis for Educational Research*. Croom Helm, London.

Bliss, J. & Ogborn, J. (1989) Tools for Exploratory Learning. *Journal of Computer Assisted Learning*, **5**, 1, 37-50.

Bliss, J., Boohan, R., Briggs, J., Brosnan, T., Brough, D,. Mellar, H., Miller, R., Ogborn, J., Nash, C., Rodgers, C. & Sakonidis, H. (1992) Reasoning supported by computational tools. In *Computer Assisted Learning* (eds. M.R. Kibby & J.R. Hartley) pp. 1-10. Pergamon Press, Oxford.

Bruner, J.S. (1960) *The Process of Education*. Harvard Univ. Press, Cambridge, MA.

Bunge, M. (1963) *Causality and Modern Science*. Dover Publications, New York.

Forbus, K.D. (1982) *Qualitative Process Theory*. Artificial Intelligence Laboratory, AI Memo 664 MIT. Cambridge, MA.

Forbus, K.D. (1985) The Role of Qualitative Dynamics in Naive Physics. In *Formal Theories of the Commonsense World* (eds. J.R. Hobbs & R.C. More). Ablex Publishing Corporation, NJ.

Holland, D. (1988) A Software Laboratory. Dynamic Modelling and the Cellular Modelling System. *School Science Review*, **69**, 248, 406-416.

Kurtz dos Santos, A.C. & Ogborn, J. (1992) A Model for Teaching and Research into Computational Modelling. *Journal of Computer Assisted Learning*, **8**, 2, 67-78.

Kurtz dos Santos, A.C. (1992) *Computational Modelling in Science Education: A Study of Students' Ability to Manage some Different Approaches to Modelling*. PhD, Institute of Education University of London.

Miller, R.S., Ogborn, J., Turner, J., Briggs, J.H. & Brough, D.R. (1990) Towards a Tool to Support Semi-quantitative Modelling. In *Advanced Research on Computers in Education* (eds. R. Lewis & S. Otsuki) pp. 185-190. North Holland, Amsterdam.

National Curriculum Council (1990) *Recommendations for Statements of Attainment for Information Technology Capability*. Department of Education and Science and the Welsh Office, HMSO, London.

Ogborn, J. & Wong, D. (1984) A Microcomputer Dynamic Modelling System. *Physics Education*, **19**, 138-142.

Ogborn, J (1990) A Future for Modelling in Science Education. *Journal of Computer Assisted Learning*, **6**, 2, 103-112.

Richmond, B., Peterson, S. & Vescuso, P. (1987) *An Academic User's Guide to STELLA*. High Performance System, Inc. Lyme.

Wong, D. (1986) *Development and Evaluation of a Microcomputer Dynamic Modelling System for Teaching A-Level physics*. PhD (Educ), Institute of Education University of London.