MODELING IN SCHOOL MATHEMATICS: GENERATING ACTIVE LEARNING ENVIRONMENTS

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ABSTRACT
Models and the modeling process are at the heart of mathematics. The paper discusses the importance of developing pupils' modeling abilities and skills in the context of school mathematics and focuses in particular on the content, structure and the educational exploitation of a set of activities constructed to serve this purpose in a computational modeling environment.

KEYWORDS
Computational models, modeling process, school mathematics, clusters of activities

INTRODUCTION

The importance of school mathematics stems from the fact that it provides people with a set of tools for dealing with the quantitative aspects of the world. This requires people to mathematize the situations they wish to study, that is, to identify the elements of the situation that are considered important for the purpose at hand and the relationships among them. In this process, the first step is moving from the perceptions and measurements of the actual situation to a verbal, basically qualitative description of the elements and relationships that hold among them. The task then becomes one of formalizing this verbal representation of the situation. This process is called modeling, whereas its final product a model of the situation.

The process of mathematization is only partially taught in school mathematics. Pupils are usually presented with descriptions of situations rather than situations themselves, carefully crafted to contain all the information needed to solve the problem. They are taught to make a list of "known" and "unknowns", that is, to identify the elements of the situation. They are then told to assign symbols to these elements and to write relationships among these symbols. In this approach, although explicit attention is paid to sensitizing children to the need of identifying elements of a situation and representing them symbolically, little or no effort is addressed to the problem of helping them to express the relationships among these elements. In other words, despite their apparent importance, models and the modeling process have a very limited place in the current school mathematics curriculum. In the following, some aspects of models and the modeling process that are considered important for the learning and teaching of mathematics are briefly discussed.

Mathematical concepts and operations are mainly abstract, formal constructions. Their meaning and coherence are guaranteed by axiomatic constraints. However, humans are not equipped to manipulate concepts and operations whose consistency is not supported by some empirical evidence. To think by manipulating pure symbols which obey only formal constraints is practically impossible. Thus, we need models, which attribute some behavioral, practical, unifying meaning to these symbols. These models tend to replace, tacitly, the original in the human reasoning process and are very often suggested by the initial, empirical reality from which the mathematical concept has been abstracted (Fischbein, 1989). The above highlight a number of aspects of a model (Fischbein et al, 1990):

- A model should act as a substitute in a reasoning process;
- There must be a certain structural correspondence between the original and the model;
- The original and the model may change their roles; however, one of the two plays usually more adequately than the other the role of the model;
- A model has a heuristic function; consequently, it should cognitively be more accessible than the original. Furthermore, it should be more adequate for a pictorial, behavioral or mechanical representation;
- Models can be intuitive or abstract; external or mental; tacit or explicit; analogical or paradigmatic; primitive or elaborate;
- A model is structurally unitary and autonomous and it unavoidably imposes its constrains on the original.

The above features make apparent the importance of models and the modeling process for school mathematics, where pupils are continuously asked to either construct or explore models in exemplifying or applying mathematical ideas. Modeling is a particularly demanding process as it requires a wide range of skills: generating relevant factors, selecting the important ones, generating relationships between factors, selecting among such relationships and posing the specific questions crucial to understanding the problem situation. Burkhardt (1984) identifies six stages in a modeling process in the context of school mathematics:

- *Formulation*: the production of a theoretical construct that mirrors some essential aspects of the situation to be modeled.
- *Solution*: the turning of the implicit statement of the model into explicit answers; it receives most attention in traditional mathematics classes.
- *Interpretation*: the translation of the mathematical answers back into the language of the situation; it usually needs some effort and skills and though relatively straightforward, it is usually neglected in current mathematics classrooms.
- *Validation*: the validation of the model's predictions by comparison with the actual situation. Here, the purpose for which the model is needed and the precision this implies must be kept in mind. Modeling with computers can be very valuable at this stage. Validation is second only to formulation in its high level demands and it is also largely neglected in mathematics teaching.
- *Improvement, extension or refinement*: the revisiting of the modeling process.
- *Reporting*: the gathering together of the results.

The above show that the range of skills required in modeling is very much wider that the one developed in traditional mathematics classes, where the students are usually given the appropriate model and asked to solve it, while formulation, interpretation and validation are rarely seriously attempted. It is obvious that for pupils to be able to successfully tackle problem situations, it will pay to develop explicitly these other skills. Moreover, as these skills involve high level strategic elements, we shouldn't expect this to be an easy task. In particular, the problems to be tackled will probably need to be very much simpler when the whole load falls on the student than when he has only the solution phase to carry. However, if we are to use mathematics effectively, we need all these skills; otherwise we are forced to accept that most of the mathematics we learn is to be of no help in tackling problems which were not studied at school. Burkhardt, discussing the main reasons for trying to teach modeling skills in school mathematics argues:

- If children are to become able users of mathematics in tackling problems, the full range of these high level skills is needed;
- Practical, everyday problems provide an extra motivation for pupils to study mathematics;
- Modeling causes the student to draw from the full range of his mathematical knowledge – and not just from one topic area (as traditional mathematics problems tend to do), thus providing practice in mathematics;
- The study of models reinforces basic mathematics understanding as well as operational skills by providing concrete illustrations of the mathematical concepts involved;

- The range of higher level skills which modeling develops is of the kind needed to solve problems within mathematics as well as outside of it, not developed by most current mathematics teaching;
- In teaching modeling in the context of mathematics, the situation to be modeled is the central interest and not the illustration of a specific mathematical technique by a practical application. No matter how valuable this latter may be, it is a quite different type of activity, requiring a much narrower range of skills.

Traditional mathematics teaching usually presents the students with a collection of practical situations and a set of models that have been found useful in describing them. The students are expected to become familiar with these standard models and to apply them to analyzing minor variations of the original problem situations. This allows for the introduction of fairly complex and difficult problems. In formulating a model of a situation, the students must themselves recognize some of its essential aspects and choose a suitable model. In doing so, they are likely to use only mathematics that have assimilated very well and to be able to handle only much simpler problems than those in traditional mathematics classes. Experience of both types of problems is important for pupils' mathematics understanding.

Concluding, modeling is a vital thinking process that helps pupils to gain insights into the real world and also make connections between various phenomena. Models are used to explain the world, to predict what might happen, to test ideas. Models are of particular interest in education, because it is the role of the teacher to provide children with appropriate representations or models in a range of domains of knowledge. Clearly, these representations should be accurate and consistent, but not necessarily complete, so that they can be assimilated (Bliss, 1994). Mathematics, being the science of models and modeling, constitutes the obvious school subject for cultivating pupils' modeling skills and consequently advancing their understanding of the subject matter. Technology, particularly information technology, can play an important role towards this direction as "to make a model on the computer is to create a world but a world which evolves or changes in front of one's eyes. It is an imaginary world which may or may not reflect something important about the real world" (Ogborn, 1990). The activities described below constitute a first attempt towards creating learning situations in a computational environment, which provide opportunities for promoting pupils' mathematical understanding through the development of their modeling skills.

PROMOTING MATHEMATICS UNDERSTANDING IN A COMPUTATIONAL MODELING ENVIRONMENT: THE SETTING UP OF APPROPRIATE EDUCATIONAL MATERIAL

The content and the structure of the material: some basic features

The mathematics activities presented in the following were designed and developed in the context of a European research project concerning the implementation of a computer-based learning environment (called ModelingSpace) in a number of areas of the late compulsory school curriculum (11 – 15 years old), mathematics being one of them. In the particular environment, pupils can either explore a model (exploratory level) or can build their own (expressive level), making use of a number of tools provided for this purpose.

Three cross curricular topics, chosen on the grounds of being familiar and interesting to children and meaningful to them in terms of task were selected: planning of a holiday, traffic accidents and field and track events. For each of these topics, a set of activities called «cluster of activities» was developed, making up a worksheet for pupils, both at the exploratory and the expressive level. In each cluster, the constituting activities:

- Develop gradually with respect to the cognitive requirements of the tasks set to the pupils;
- Focus initially on the real situation, moving progressively to more abstract levels, in order for the modeling of the situation at hand to become possible;
- Attempt to first draw pupils' attention to the qualitative features of the situation, then to the semi-quantitative and finally to the quantitative ones. This is the way the human mind works when trying to understand and model a situation or a phenomenon.

The activities of each cluster concern aspects of the modeling process, but, at the same time, they aim at providing opportunities to the pupils for studying fundamental mathematical ideas, grasping their functionality and being initiated into the way the mathematical knowledge is organized and represented (see previous section). Drill and practice in computational algorithms and in the application of rules do not usually constitute a subject of study in these activities.

For each topic, the cluster of activities do not differ very much from grade to grade but to the number of activities included and the level of difficulty of the tasks set. The total number of clusters developed at both the exploratory and the expressive level appear in table 1 below.

Table 1. Clusters of activities per topic, mode of modeling and grade

Topics per type of modeling environment	**Clusters of activities per grade**			
	6th grade (12 years old)	7th grade (13 years old)	8th grade (14 years old)	9th grade (15 years old)
Exploratory				
Planning a holiday	✔	✔	✔	
Accidents- crossing a road		✔	✔	
Accidents - driving		✔	✔	✔
Field and track events		✔		✔
Expressive				
Planning a holiday	✔	✔	✔	
Accidents		✔	✔	
Field and track events		✔		✔

Designing and developing the clusters of activities: some theoretical considerations

It is generally recognized today that learning is not only an individual process of active meaning construction. Social and cultural factors as well as human practices and material constructs also play a significant role in defining the boundaries and determining the way in which the individual approaches the mathematical knowledge (e.g., Bliss & Saljo, 1999, Cobb & Bauersfeld, 1995, Cobb et al, 1993). This is the basic perspective within which the design and the development of the clusters of activities described above were developed.

More specifically, the approach adopted for the constitution of the clusters was based on a combination of a constructive as well as a socio-cultural view to teaching and learning mathematics. With respect to the first, Piaget advocated that the development of the mind is the result of the interaction of the individual with his/her environment. The existent thinking processes or cognitive structures either assimilate every new stimulus or, if this is not possible, they are modified in order to accommodate it. In particular, between the age of 12 and 18 years old, the thought suffers a qualitative change that takes it at higher levels, where the child is capable of using abstract thinking. The latter allows him/her to produce an idea or a model of events that have been previously described using concrete operations and to check its validity. The activities of the clusters generated for the purposes of the project contribute to the passage from thinking in terms of concrete operations to thinking in abstract terms, as they encourage reasoning norms typical of the latter, e.g.:

- Control of the variables and elimination of the irrelevant ones
- Ratio and Proportion
- Probability and correlation
- The use of abstract models to explain and predict.

Vygotsky (1986) was among the first to suggest that Piaget's view that the intellectual development is accomplished through the process of accommodation is inadequate. From the time of his/her birth, adults (initially his/her parents) facilitating his/her learning and the development of his/her abilities surround a child's world. This process, called by Vygotsky mediation, is very important for the child's natural development. When the mediation of the adult between the world of the child's immediate senses and his/her developmental course is appropriate, s/he becomes confident about her/his abilities to learn from the surrounding environment and in this case what Piaget described takes place. However, Vygotsky believed that for many children, the mediating experience is not an appropriate one. He advocated that school and in particular teaching should offer to pupils opportunities of working not only at the level at which they are temporarily capable of, but also further than it. Consequently, teachers as mediators need to become aware that it is very important to act less as models to imitate and more as managers of learning in small groups and in the class as a whole. This needs to be done in such a way as to considerably increase the possibility for a child to witness in another child the step next to the one where his/her thought is. Vygotsky suggested a socio-cultural approach to teaching and learning, where the adult teacher via the social practices and the cultural tools of the society s/he lives in facilitates the learner to gain access to knowledge. We believe that the activities of the clusters described in the previous section and the guidelines to the teachers sketched below are compatible to Vygotsky's ideas and formulate a framework that offers to the pupils essential opportunities for developing mathematical understanding and skills of the kind discussed in the introduction.

THE UTILIZATION OF THE EDUCATIONAL MATERIAL IN THE MATHEMATICS CLASS: SOME SUGGESTIONS

The teaching approach adopted in using the clusters of activities in the classroom aims at functioning in a manner complementary to the one followed at school during the teaching of the respective units, reinforcing and substantiating pupils' understanding of the mathematical ideas involved. The latter are materialized via the process of modeling and the emphasis placed upon mathematical reasoning in the tasks set. In general, the constituting activities of the clusters attempt to shape a learning environment, which encourages and supports the re-discovery of the mathematical ideas and thus the re-construction of the mathematical meaning by the pupils themselves.

More specifically, in exploiting the material in the classroom, the teacher is asked to bear in mind the following:

- Students are invited to carefully study each activity before they start working on it and to co-ordinate with their fellow students and their teacher if necessary during its processing. It is hypothesized that this approach has considerable and long-term effects on the pupils' way of thinking, formulating a stable basis for higher performance in the subject matter.
- Despite the fact that each cluster of activities focuses on a set of particular mathematical ideas, the target of the respective lesson is not so much the learning of these ideas as the process of approaching them through modeling real or theoretical situations and phenomena.
- The emphasis of each lesson should be on the students working in small groups or interacting with the whole class, formulating arguments, justifying views and accessing the fundamental parameters as well as the complexity of the relevant mathematical ideas. The outcomes of each teaching period with the clusters should be more about the processes of thinking and reasoning mathematically and less about the actual mathematical knowledge and skills involved.

In exploiting the clusters of activities within the classroom, the teacher should principally ensure that all students understand and appreciate the questions asked and the challenges set by the activities. It is important to allow each pupil to respond in his/her own way to these challenges, guided when absolutely necessary and only with respect to the appropriate selection of the challenge to pursue in relation to the mathematical structure and the communication of ideas and outcomes.
Most of the students who the material is designed for are expected to respond successfully, even if partially, to the activities. However, if some of the activities are proved exceedingly demanding for some students, they can be altered respectively by the teacher.

Table 2 below presents the units of the mathematics curriculum, which the activities of each cluster focus on.

Table 2. The mathematical focus of the cluster of activities per grade

<table>
<tr><th>Clusters of activities</th><th>Mathematical focus</th></tr>
<tr><td>Planning a holiday
(3 versions: 6th grade,
7th grade, 8th+ 9th grades)</td><td>Primarily: Ratio, Proportion, Percentages
Secondarily: Operations with rational numbers, Calculation of arithmetic expressions, Variables, Algebraic expressions, Formulae, Linear equations and functions, Representation, processing and interpretation of data, Mean, Problem solving.</td></tr>
<tr><td>Accidents: Crossing a road
(2 versions: 7th grade,
8th+9th grades)</td><td rowspan="2">Primarily: Variable, Equations of 2nd degree, Functions of the form $y=ax^2+bx+c$ and $y=a/x$
Secondarily: Operations with rational numbers, Ratio and proportion, Rate of change, Representation, processing and interpretation of data, Mean, Problem solving.</td></tr>
<tr><td>Accidents: Driving
(3 versions: 7th, 8th and 9th grades)</td></tr>
<tr><td>Field and track events
(2 versions: 7th+8th grades,
9th grade)</td><td>Primarily: Algebraic expressions, Functions of the form $y=ax^2+bx+c$ and $y=a/x$
Secondarily: Operations with rational numbers, Powers, Rate of change, Representation, processing and interpretation of data, Mean, Problem solving.</td></tr>
</table>

Each cluster of activities may take 90 to 180 minutes (that is, two to four teaching periods respectively) to complete. However, more time may be spent the first time.

The constituting activities of each cluster develop in four phases (Appendix I offers part of the cluster of activities developed around the topic "Planning a holiday"):
Phase 1: The lesson usually starts with an *introduction*, the role of which is to help the student get acquainted with the wider context within which the constituting activities are situated, without the presence of the computer. This part of the lesson aims at defining the situation, the event or else problem about to be modeled as well as the purpose of this procedure. The language used and the broad scope of the activities have been selected in such a way that all students can respond to in some degree.

Phase 2: The activities that follow right away focus student's attention on the *qualitative* study of the basic factors (elements) determining the situation (and the subsequent model) as well as on the simplification of the specific situation. The aim of this phase is: a) to render modeling possible, b) the model to be as close to reality as possible allowing at the same time the clear, effective conception of it. Thus, this phase attempts to enable students not only to define variables but also to recognize the existing relationships.

The mathematical ideas are not yet directly recognizable in this phase but their main qualitative features start appearing. For instance, the notion of part-whole, which constitutes an essential component of the concept of percentage appears in the study of the topic "Planning a holiday". Moreover, the student is offered the opportunity to realize one of the fundamental stages in the problem solving process, i.e., the semantic analysis of the written scenario and its reduction to a " mathematized" environment.

Phase 3: The activities in this phase focus on the *semi- quantitative relations* of the entities-variables that emerge (at the exploratory level) or are about to appear (at the expressive level) in the model. The phase aims at helping students define "the direction" of the relationships, in other words, in what way the variables co-change.
The mathematical ideas the cluster of activities focuses on start becoming more distinct. For instance, in the study topic of " Accidents", linear and non-linear relationships (e.g. proportionate) of variables,

which will help in the construction and study of the exact equations in the next phase, are identified. Moreover, the activities in this phase can help the student realize, appreciate and become familiar with:

- the relation of mathematics to every day life
- the formation of mathematical concepts
- the necessity of mathematics
- the main features of abstract thinking and mathematical reasoning such as variable control, prediction and correlation of variables.

Phase 4: The activities in this phase focus on the specification of the *quantitative features* of variables, their relations and their representation in such a way that they can be used in modeling. The aim in this phase is to help students define with (quantitative) precision the way variables are related.
This phase might as well be characterized as the phase of "par excellence mathematization" of the situation, since entities and their interrelations are turned into numerical, algebraic or geometrical. This allows the student to examine the model's behavior more effectively, based on the symbolic representation of the variables and their interrelationships.

Phase 5: The last part of each activity group focuses on the *experimentation/ testing and improvement* of the model that is being examined or has been constructed. In order for this to happen, the student is asked, among other things, to "run" the model using different ways of representing the data as well as the results. From a mathematical point of view, the emphasis in this phase is put on the way the different means of representation operate\function in mathematics. In other words, in this phase, the student is encouraged to explore how the symbolic character of mathematics allows (or hinders) access to mathematical knowledge.

The above show that in general, the constituting activities of each cluster become harder with respect to their cognitive demands as they develop one after the other. However, it is up to the teacher to modify appropriately any activity, which s/he would consider necessary, in order to make it possible for all students to get involved with the activities at some level. Finally, it should be pointed out that a cluster of activities considered appropriate for a particular grade can be also given to students of a lower or even higher grade, if the teacher judges that this will be beneficial to them.

SOME CONCLUDING REMARKS

The development of each cluster of activities presented above, particularly in the first three phases, is based on the premise that problem solving experts at first think qualitatively and then try to describe quantitatively the problem data and how they are interrelated. This practice leads to qualitatively higher representations, which allow the expert solvers to know when qualitative reasoning is not sufficient and quantitative reasoning is necessary. This, of course, does not mean that the experts use qualitative reasoning whereas the novices do not. What it means is that the experts' reasoning moves to a semantically deeper level than novices' does, incorporating content principles of the specific field. Inexperienced solvers' reasoning is based on the superficial structure of the problem and is directed to form and procedure comparisons in an attempt to isolate the "unknowns" of the problem.

Qualitative reasoning has an intuitive character in the sense that it is based on real experiences and secures important flexibility in thought. Consequently, the teaching of mathematics will have much to gain if it will present students with activities that will help them start building up qualitative reasoning skills. This is because qualitative reasoning may guide students' quantitative thinking the way this happens with problem solving experts. Obviously research only can establish the way in which both knowledge of the principles of qualitative reasoning and the ability to use qualitative reasoning help students relate this intuitive, informal knowledge to the symbolic system which constitutes the basis of the quantitative methods, hence mathematics. Bearing the above in mind, the clusters of activities developed for mathematics in the context of the project "ModelingSpace" offer to the students significant opportunities to develop principles of qualitative and quantitative thinking and reasoning, both of which are at the heart of the meaning construction process in mathematics. We are currently using these clusters of activities in a number of primary and secondary classes and we collect data, the analysis of which will hopefully allow us to evaluate their actual potentiality.

APPENDIX

An example of a cluster of activities

(Only certain parts of the cluster are shown)

Theme of Study: Planning a holiday
Type of activity: Exploratory
Pupils 12-13 yrs old

Every year, thousands of people all over the world organize holidays and trips to different destinations. The development of mass transport has reduced significantly the cost of traveling and has thus permitted more people than ever, from every social class, to satisfy their desire to travel and visit other places.

1. Suppose that you decide to organize your summer holidays ahead of time. Discuss and decide on the *factors* that you think you should take into consideration so that you can calculate correctly the *total cost* of your trip. Based on this discussion, try to answer the following questions:

- Which factors you think you should take into account, so that you can estimate correctly the cost of your trip?

…… (omitted)

2. In the file entitled "travelling cost" you can find a model for calculating the total cost of the trip.
Suppose you are a travel agent and you have a client (from the same town as you), who asks you to find out how much it would cost him and his wife to go on holidays the following month for 5 days on a Greek island, staying in a Category B hotel.

- Use the model in the "travelling cost" file to find the cost of the holiday. You can make use of relevant information published by travel agencies in the morning press, in brochures or on the Internet (e.g. www.greekhotels.gr or www.cretexports.com, etc).

……. (omitted)

- Do you believe that this model contains the entities and relationships necessary to calculate with precision the cost of the trip? Explain.

…… (omitted)

- Do you believe that the total cost of the trip can be reduced or increased, without changing what the client has requested? How?

…… (omitted)

- Some people maintain that in a trip, the largest part of the cost is the accommodation cost (e.g. hotel), whereas others assert that it is the transportation cost (e.g. airplane fares, etc.). What do you think?
- The two tables below present different airplane fares to Chania (Crete) and different hotel prices there for two different periods in 2001 and 2002 respectively.

…… (omitted)

- How much was the increase (expressed as a percentage %) of the daily accommodation cost in a hotel in March 2002 compared to March 2001?

…… (omitted)

- What will happen to the cost of the trip in the following situations and why?
    - (a) If the duration of the trip *increases twofold* from 5 to 10 days?
    - (b) If the destination was the town of *Ioannina*?
    - (c) If your client chooses not to go by airplane?

3. Suppose that your client informs you that his wife and he can spend up to the amount of 1100 Euros and asks you to make different suggestions about where in Greece they could go for 10 days of Christmas holidays.

- Use the model, to put together 2 – 3 proposals. For help, you can use relevant information published by travel agencies in the morning press, in brochures or in the Internet. Then complete the following table:

…… (omitted)

- Which was the most worthwhile proposal and why? Which do you think that guarantees your client the most enjoyable holidays?

…… (omitted)

- For each one of your proposals above answer the following questions:
  (a) Which of the *entities* has the *biggest contribution* to the total cost of the holidays of your clients? Could you describe the *relationship* between the two, expressed as a percentage (%)?
  (b) Which *entity* has the *smallest contribution* to the total cost? Could you describe the *relationship* between the two, expressed as a percentage (%)?

…… (omitted)

4. In addition to the initial way of representation/presentation of your model, which you can see on your screens, you could also represent it in different ways, which in some cases may help you to explore better the way it works. So:

- Use the command, which creates *bar charts (or tables or graphs)* and choose the following variables: accommodation, duration, transportation and people. What can you observe concerning the *relationship* between:
  (a) accommodation cost and duration;
  (b) accommodation cost and number of people;
  (c) transportation cost and total cost;
  (d) accommodation cost and total cost;
  (e) total cost and number of people or days.

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