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Challenges and opportunities in analysing students modelling

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ABSTRACT

Modelling-based teaching activities have been designed and analysed from distinct theoretical perspectives. In this paper, we use one of them – the model of modelling diagram (MMD) – as an analytical tool in a regular classroom context. This paper examines the challenges that arise when the MMD is used as an analytical tool to characterise the modelling process experienced by students working in small groups aiming at creating and testing a model of a sedimentary basin from the information provided. The study was conducted in a regular Biology and Geology classroom (16–17 years old students). Data was collected through video recording of the classes, along with written reports and the material models made by each group. The results show the complexity of adapting MMD at two levels: the group modelling and the actual requirements for the activity. Our main challenges were to gather the modelling process of each individual and the group, as well as to identify, from students' speech, which stage of modelling they were performing at a given time. When facing such challenges, we propose some changes in the MMD so that it can be properly used to analyse students performing modelling activities in groups.

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Introduction

In recent years, research in science education has highlighted the need to engage students in scientific practices with a dual purpose: to improve their knowledge *of* and *about* science. According to Osborne (2011), these practices fall into three main groups: (a) experiment design, data collection and analysis; (b) development of explanations using models and theories; and (c) evaluating the explanations, which entails making a critical and reasoned analysis of the previous two stages. The practices related to the development of explanations based on scientific models are addressed in the educational proposal presented here.

Around the word, the contemporary standards have emphasised the need for students to develop scientific explanations. 'Explaining phenomena scientifically' is included in the PISA report (OECD, 2006), which promotes the useful learning of sciences as one of the

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three pillars of scientific competence, referring to students applying their scientific knowledge in their explanations. Similarly, the report by the National Research Council (2012) emphasises that by asking students to develop their own coherent explanations for a phenomenon, they have to incorporate their scientific knowledge or the models that represent them in order to make their explanations consistent with available evidence.

The explanations of phenomena are supported by models because, as Giere (1988) indicates,

> What science provides for 'scientific explanations' is a resource consisting of sets of well-authenticated models. How people deploy those models in the process of constructing or understanding explanations depends on the extra scientific context. (p. 105)

Therefore, the modelling process (construction, review and use of models) may promote science learning because it requires students to construct explanations of scientific phenomena, to review problems, as well as to find and to use data as part of their scientific reasoning (Maia & Justi, 2009).

A description of how modelling takes place has been proposed by Justi and Gilbert (2002), who developed a model of modelling diagram (MMD). Since these authors presented the MMD, several studies have used it, mainly for the design of educational proposals that support the use and review of models. These include the work of Mendonça and Justi (2011) and Gilbert, Justi, and Queiroz (2010) in which they investigate aspects related to the learning of content and visualisation by students learning ionic bonds from a modelling-based didactic sequence; or the study by Maia and Justi (2009) in which a modelling-based didactic sequence on chemical equilibrium is proposed and the contribution to the learning of the related contents is analysed. Another application of the MMD is discussed in Mendonça and Justi (2013) who use the MMD to analyse how argumentation permeates the entire modelling process.

The contribution of the current paper follows the use of the MMD as an analytical tool for modelling in a regular classroom context. This is done in order to deepen the steps followed by students when they are involved in a modelling activity. Our interest in using the MMD lies in the fact that it: (a) makes it possible to analyse the high-level interactivity that modelling has in small groups; (b) allows visual representation of this process; and (c) helps deepen the understanding of how students model from the point of view of understanding which information they are using and which difficulties they present in the construction and revision of a model.

In order to study how students perform a modelling-based teaching (MBT) activity, a Spanish regular Biology and Geology class was involved in an activity in which students, working in small groups, had to produce and use their mental models to develop a material model of a sedimentary basin. The students were asked to produce a material model as an excuse for creating a verbal model of how sedimentary basins are formed and, in turn, reviewing their mental models. In order to help them start thinking about the system, the activity provided them with some data that could be used to create the material scale model (i.e. that in which there is an attempt to represent the elements of the real system while maintaining the ratio between them (Harrison & Treagust, 2000)). The main purpose of this paper is to discuss the challenges we faced when using the MMD to analyse the modelling process of a sedimentary basin performed by students, as well as how we adapted the MMD so that we could reach our aim.

Geology is a discipline that has an important abstract component because many natural processes that are studied are not easily observed (Reynolds et al., 2005). This means that most of the phenomena, such as the formation of a sedimentary basin, are not perceived during an individual's life. On the other hand, we can think of the speed with which an earthquake occurs, whereby the representation of these phenomena for viewing and understanding becomes important. The part of geology addressed here is stratigraphy, in particular the formation of sedimentary basins where sediments have been deposited to form the layers. Therefore, we consider it essential to use modelling as a teaching strategy as it may help students to visualise phenomena that occurred millions of years ago.

Models and modelling

Models are important in science mainly because we can use them to generate explanations and predict events that take place in the natural world. Any cognitive construct used to respond to a question involves the use of an explanatory model, which can be more or less consistent with the scientific model.

From the definitions proposed for the concept 'model' (Gilbert, Boulter, & Elmer, 2000; Megalakaki & Tiberghien, 2011; Schwarz et al., 2009, among others), it can be seen that, in general, a model consists of a partial representation of an object, event, process or idea. That representation results from a set of ideas that interrelate in the mind of each individual and may be externalised through speech or visual elements. This study adopts the definition of model as the representation of a phenomenon created with a specific purpose, in which the *phenomenon* is understood as part of a whole, and the *specific purpose* is the explanation of something in particular (Gilbert, Boulter, et al., 2000).

There being a variety of models, we follow the ontological classification proposed by Gilbert, Pietrocola, Zylbersztajn, and Franco (2000), by focusing on mental and expressed models, as they are relevant for the subsequent analysis.

Mental models are internal representations of how a phenomenon takes place and, therefore, they are personal (Duit & Glynn, 1996). Johnson-Laird (1983) describes these models as analogical structures of how we perceive and conceptualise the world. Given their individual and internal character, such models are not accessible to the researcher or teacher. Therefore, it is impossible to completely characterise them. Thus, we use expressed models, that is, that version of the mental model that is communicated by the individual (Gilbert, Pietrocola, et al., 2000). Franco and Colinvaux (2000) emphasise that, when analysing an individual's model, it is important to take into account certain characteristics of mental models: (a) they are generative, that is, they make it possible to produce predictions and new ideas; (b) they include tacit knowledge, thus those who have the mental model may be unaware of each of the aspects that constitute their mental model; (c) they are synthetic, that is, they are simplified representations; and (d) they are limited by the people's views of the world and beliefs. Thus, one of the main functions of mental models is to allow the subject to perform explanations and predictions about the system represented by the model.

In the educational context, students' mental models contain their own ideas about how phenomena occur, or preconceived ideas on how scientific knowledge is constructed

(Grosslight, Unger, Jay, & Smith, 1991). This emphasises the need for involving students in modelling in science classes since it may be a fundamental activity for learning and using scientific concepts, and a key method for supporting conceptual change (Megalakaki & Tiberghien, 2011). This is so because the explanatory models used by students are constituted by a structure of beliefs and images that is generative, that is, it allows them to integrate new information, make predictions, act and generate new knowledge by thinking with such models (García-Rodeja Gayoso & Lima de Oliveira, 2012).

Therefore, the fact that students are able to generate mental models is vital because it plays an important role in their learning process, since it facilitates the learner's cognitive engagement with what is being taught, and helps him/her interact with the new information (Gilbert, 2005). This was revealed by studies like Vosniadou and Brewer (1994), in which the authors analysed the students' models of the day/night cycle and perceived a change in their initial mental models as they acquired knowledge about the subject (which meant that some students approached the scientific model). This reinforces the idea that students explain the world using their mental models (Gilbert, Pietrocola, et al., 2000).

Mental models are externalised from the use of various modes of representation: concrete or material, verbal, visual and gestural (Boulter & Buckley, 2000), thus resulting in the production of *expressed models*. The development of such models takes place through modelling, a process that is understood as the construction of new models, or as the review and evaluation of existing models (Morrison & Morgan, 1999).

In the science literature, the general process of construction, revision and evaluation of models is known as modelling. In accordance, in the science education literature, the general phrase *MBT* is used to identify a teaching situation in which students are involved in modelling activities.

In the literature, there are some proposals concerning the participation of students in different kinds of activities involving models and/or modelling, or presenting theoretical frameworks that may support the promotion of MBT (for instance, Clement, 1989; Clement & Rea-Ramirez, 2008; Gilbert & Justi, 2016; Halloun, 2004; Justi & Gilbert, 2002; Lehrer & Schauble, 2012; Passmore & Stewart, 2002; Svoboda & Passmore, 2013; Windschitl, Thompson, & Braaten, 2008). As our study is based on the framework proposed by Justi and Gilbert (2002), we explain it in order to both justify our choice and support the readers' understanding of our study.

From studying the role of models and modelling in the development of scientific knowledge, Justi and Gilbert (2002) identified four main general stages for modelling and created the MMD. In the MMD, the stages are also cyclical and connected by two-way relationships, representing the great interactivity among them. Broadly speaking, as shown in the diagram in Figure 1, the modelling process would start from the definition of a clear purpose for building the model (Justi, 2006). Then, the individual would need to bring his/her previous experiences concerning, or related to, the entity that is being modelled, and to analyse them in the light of the previously defined aim. Furthermore, to produce an initial mental model, it is sometimes necessary to take elements from the natural world. This comprises the substage 'selecting the source of the model' which, according to Justi (2006), corresponds to the use of both aspects of reality to draw analogies or mathematical resources that may help in the creation of the initial mental model. After producing a given mental model (stage 1), the 'expression of the mental model

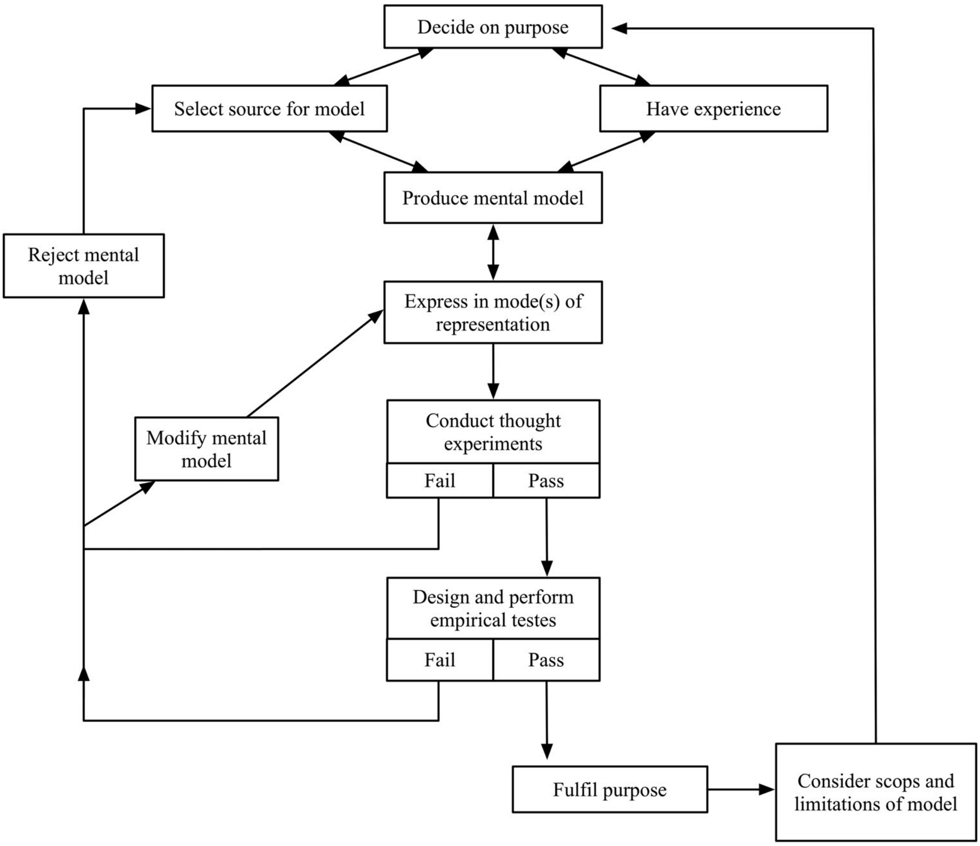

Figure 1. Model of modelling diagram (MMD) (Justi & Gilbert, 2002, p. 371).

through some form of representation' occurs (stage 2). This stage is very important because the individual must be able to communicate his/her mental model to others. It also encourages the individual to reflect on his/her own mental model and, possibly, modify it. This justifies the two-way relationship between the production of the mental model and its expression. In the MMD, there are two ways of testing the model (stage 3), that is, to check whether, or to what extent, the model fulfils its purposes: one that occurs exclusively at the cognitive level (thought experiments), and another that involves the empirical level. Thought experiments are performed by asking 'what if … ?' questions in order to check whether the assumptions included in the model can be accepted, modified, or rejected (Justi, 2006). The second type of test –'designing and conducting empirical experiments'– involves the use of practical activities, in which data are collected and analysed (Justi, 2006). Finally, the MMD considers the importance of testing if the model is valid in a distinct context (stage 4). This is done by discussing its scope and limitations, thereby contributing to develop the modeller's critical and scientific thought.

Recently, Gilbert, and Justi (2016) have created a new representation for the MMD using a tetrahedron to emphasise the relationships between the four modelling stages (creation, expression, test and evaluation), where each of them corresponds to a tetrahedron vertex. Nevertheless, we use the initial version (Figure 1) because it was the one available when the study that based this paper was conducted.

Assuming the importance of students learning science in a broader way, that is, learning about the practices involved in the production and use of scientific knowledge, Justi and Gilbert (2002) propose to use the MMD as a basis for designing modelling-based science activities. From our viewpoint, the main advantage of using this diagram to base a science teaching approach is the possibility that such an MBT would have to help students understand the process of generating scientific knowledge as a non-linear, dynamic, subjective and continuous one.

Aims

From the issues discussed above, as students build internal representations, mental models to explain the world around them, MBT helps them both to explain their mental models, so that they can be evaluated by their peers or by the teacher, and to check if their model can be used to explain the phenomenon in question. Both aspects are essential in the science learning process (Gilbert et al., 2010) since they support the development of students' knowledge. MBT from the perspective of the MMD reflects the fundamental issues of modelling, that is, the construction of mental models from the interaction of students' prior knowledge; and the continuous revision of the students' models from the addition, reduction or modification of ideas that compose them (Dolphin & Benoit, 2016).

In order to get this, students are fostered to work collaboratively. From socio-cognitive perspective, this means a situation in which students share and transform their knowledge as a result of interactions between them (Oliveira & Sadler, 2008). As these authors have indicated, when participating in collaborative activities, like the modelling-based ones, students share concepts and perspectives of the phenomena under study, which contributes to the growing of their knowledge. Therefore, students working collaboratively are seen as an analogy of small scientific communities in which scientific knowledge is produced (Bell, Urhahne, Schanze, & Ploetzner, 2010). Additionally, when working in small groups, students have opportunities to express themselves among peers, discuss and exchange views or construct meanings, that is, create a space in which they 'talk science' (Lemke, 1997). In particular, MBT contexts may support students' engagement in inquiry-focused task, in which they have to articulate their mental models with those from their peers, negotiate meanings, argue in order to convince others of the validity of their own ideas.

Consequently, in order to understand students' knowledge construction in MBT contexts, it is important to consider that their participation involve, mainly, collaborative work. This aspect was not clearly considered in previous studies based on the MMD (for instance, Maia & Justi, 2009; Mendonça & Justi, 2011). As it is clear from the previous characterisation of the MMD, it considers modelling as an individual process. In fact, although the above-mentioned studies show that the MMD is a valuable framework to support the planning and conduction of MBT, their authors recognise that the absence of considering possible students' interactions is the main limitation for using the MMD as an analytical framework. That is the focus of the main challenges that we face in this paper.

Therefore, this paper aims at enhancing the discussion concerning the use of the MMD to support the analysis of MBT contexts by focusing on a dimension related to the modelling process based on students' speech, especially when working in groups. This implies that the MMD has to be focused simultaneously on the group and on the individual level. Considering this aspect, the paper discusses the following research questions:

(1) Which challenges can be faced when adapting the MMD for characterising the modelling process carried out by students working in groups?
(2) Which challenges can be faced when implementing the adapted MMD as an analytical tool?
(3) To what extent does the analysis conducted from the adapted MMD promote a more comprehensive understanding of the modelling process carried out by students?

By discussing such research questions, we contribute to the literature on MBT not only from the knowledge produced in this study, but also because such knowledge might foster additional discussions on how students may construct knowledge while interacting to each other during participation in MBT activities.

Methodological aspects

General information about the study

The study was conducted in Spanish secondary education classrooms (1st-year baccalaureate, 16–17 years old students) with 16 students who worked in groups of four individuals each. The sample for this paper are groups B and J ($N = 8$), since, given the involvement of students in intense discussions, they are the ones whose analysis better show the potential of the MMD as a tool to analyse the modelling process. The names of each participant have been replaced by pseudonyms beginning with the letter of the group they belong to, and the gender of the students was maintained.

It is a qualitative study, a case study, because it analyses the experiences of students working in groups, their interactions and the texts they write in order to discover their knowledge or skills (Gibbs, 2007), in this case related to modelling. More specifically, a discourse analysis was made to access the students' knowledge and skills during problem solving in geology and to understand their ability to develop modelling processes through their speech. As van Dijk (2012) indicates, the mental models of individuals play a central role in their speech and, in turn, through speech people interact with others, establishing learning communities, which implies modification and revision of their mental models.

The context: 'Reconstructing the sedimentary basin of As Pontes'

The task in which students were involved is a modelling-based activity, that is, one in which students have to produce, test, use and discuss their models identifying their limitations (Justi & Gilbert, 2002), although the MMD was not specifically considered for its design.

In the task (Appendix), students are asked to develop a material model that reconstructs the sedimentary basin of As Pontes (located in A Coruña, Galicia), by interpreting three stratigraphic columns taken from geological studies by Barsó, Cabrera, Marfil, and Ramos (2003) before the basin was exploited to extract coal. To do this, students have to mobilise mental models concerning the meaning of a sedimentary basin, that is,

> portions of the earth's crust that have been nonlinearly down-warped and filled with sediments during intermittent relative uplift and subsidence. Although most people recognise that basins are reservoirs for petroleum, their strategic reserves of metals are generally less recognised. (Kyser & Hiatt, 2003, p. 139)

They have also to identify the strata, that is, the sediment layers that fill the basin; and to apply dating methods: the *principle of superposition of strata*, where each stratum is older than the one above and younger than the one below; and the *principle of lateral continuity of strata*, where, as a rule, sediment layers are deposited horizontally (Tarbuck & Lutgens, 2005) while maintaining the same age across their expansion.

The activity was part of the educational programme of the subject 'Biology and Geology' and students were previously instructed in the relevant contents of geology (e.g. the sedimentary process, the meaning of stratum, geological dating, geological time, among others). Thus, this activity complemented the previous teaching. The students carried it out in a 50 minutes session. The activity was designed by the first author, and discussed with the teachers who participated in both the pilot and the main study. The activity was validated in a pilot class whose students have the same age of those who constituted our sample and were studying the same subject. From the pilot study, we determined the time required and whether the degree of difficulty of the activity was appropriate for that educational level.

Data collection and analysis

After students' parents have given a written consent to the conduction of the study, we register each group discussions in audio (by using a recorder) and in video (by using a camera). The first author transcribed the audio supported by video information. Both sources allow us to envisage how the group works, especially regarding who was talking at a given moment, the purpose for which s/he is doing it, and the material s/he was referring to. These considerations were registered in brackets in the transcripts. Such transcripts, as well as the students' written reports, the material models built by each group, and field notes produced by the first author about the events occurred during the lesson constituted the set of data analysed in this study.

The lesson from which the discussions were recorded was one of a series of lessons recorded by the first author. So, when data were collected, students were used to the presence of the researcher and the camera/recorder in the class.

The validity of the study was ensured by data triangulation (Stake, 2003), comparing all sources of data, that is, the audio-visual recordings, the written material, the concrete models and the field notes to check if the same, or complementary, information was obtained. This analysis was conducted by two of the authors independently and was discussed until an agreement was reached. Subsequently, the study was reviewed by relevant researchers in the field of modelling in science education, and additional necessary changes were agreed.

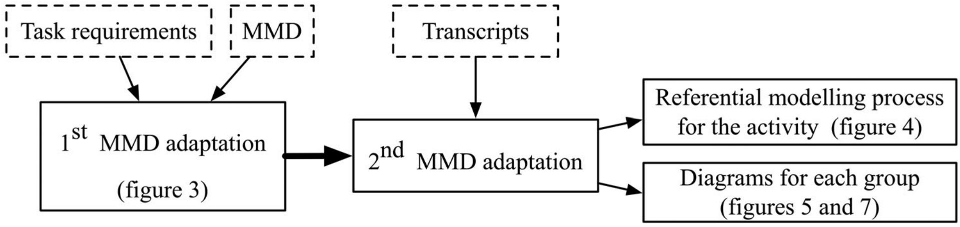

Figure 2. Analysis of the modelling process.

The data analysis was performed in several steps, summarised in Figure 2:

(1) General analysis of the whole set of data in order to identify the modelling stages required in the activity. In other words, we tried to use the MMD to support the analysis of the empirical data, which resulted in the identification of some needed adaptations of the MMD. This supported the initial discussions concerning our first research question.
(2) Analysis of the students' discourse from the transcripts of each group discussions by trying to separate the students' speech according to the modelling stages predicted by the MMD. This resulted in a second adaptation of the MMD in order to include specific aspects of the students' modelling process. This was done by producing a general reference modelling diagram, that was then used to produce specific diagrams representing the modelling process carried out in each group. This allowed us to complete the discussion of the first research questions, as well as to discuss the second research question.

Due to the nature of the research questions addressed in this paper, in the next section we present a detailed description and justification of the adaptations of the MMD, as well as the outcomes we reached, including some transcripts as examples to illustrate our interpretation about how the groups generate the sedimentary basin model.

Results and discussion

The process of adapting the MMD

The choice of the MMD (Justi & Gilbert, 2002) as an analytical tool is based on the fact that it allows us to characterise the modelling process carried out by students iteratively, that is, not as a linear process; and it shows how the stages of modelling occurred during the task, which is essential to better understand how the process takes place in each group.

When we first tried to use the original MMD (Figure 1) as an analytical tool, it emerged the need to adapt it to include two general aspects. One is related to the fact that students were performing the modelling activity in groups. This means that we would have to find a way to represent not only individual mental models, but also the interaction between each express model into the group consensus model. As we previously emphasised, this is a limitation noticed in previous studies that used the MMD. Another aspect comprises

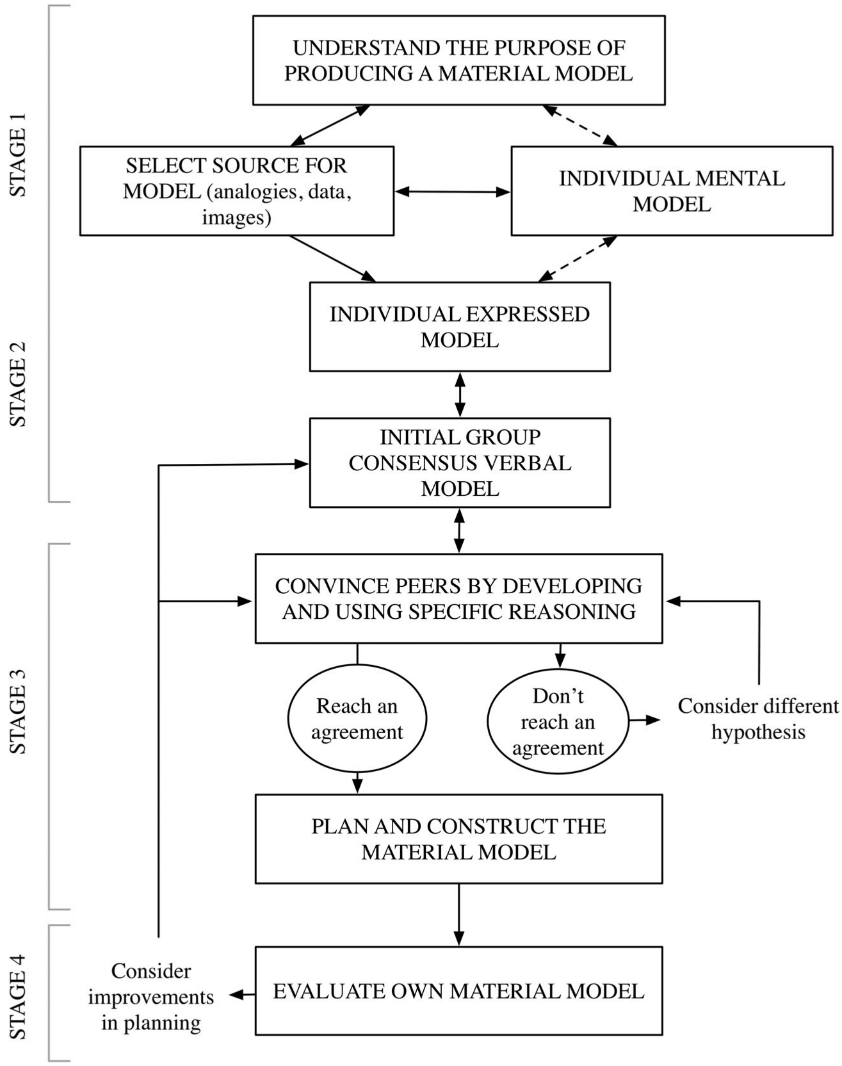

Figure 3. Adaptation of the model of modelling diagram (Justi & Gilbert, 2002), for analysis of modelling in groups. Dotted lines: implicit relationships. Solid lines: explicit relationships.

the specific requirements of the proposed activity (as explained in the following paragraphs). This resulted in the adapted scheme shown in Figure 3.

As for *modelling in groups*, this adaptation requires modifications that do not consist simply of considering the group instead of the individual as the subject of the actions. It was necessary to consider the existence of interactions between the mental and expressed models of each individual, while these individuals interact with each other at a group level. Thus, the first stage of the MMD is that which has been modified further, as it can be seen from the comparison between phase 1 of the original (Figure 1) and of the adaptation we propose (Figure 3). Such a change is justified by the fact that the mental model of each member interacts with the information provided and is expressed in the 'individual expressed model'. Expressed models are part of the original stage 2. In our adaptation of the MMD, we show that the 'individual expressed model' of each member of the group interacts with each other, resulting in the 'group consensus model'. In other words, the initial group consensus verbal model is developed (which would be part of stage 1) while it is being expressed (which means stage 2). Since these two stages are closely interrelated, it is difficult to maintain the entity of each one in the diagram, which resulted in their unification under the same bracket in Figure 3. Additionally, at this point, the group's expressed model could change the mental models of the individuals themselves. In Figure 3, this is represented by the solid double arrows. The dotted lines represent implicit relationships between elements, that is, it is assumed that these steps are closely related, but, as they involve mental models (for instance, the arrows linking 'individual mental model' with 'individual expressed model'), it is not possible to have data to show them.

As for *the requirements of the activity*, the adaptation consists of accommodating the stages of the MMD to the stages required in the proposed task. This adaptation was performed in stage 3 because only mental test is required, that is, 'conduct thought experiments' according to the MMD. So, we substituted this element of the MMD for one that represents better how the test stage was conducted: 'to convince peers through specific reasoning'. When so doing, students discussed why the expressed model was valid or not before building it as a material model. Finally, we changed the analysis of the limitations of the model into 'evaluate own material model' because at that stage students had to indicate whether, and how, the final material model addressed their pre-planning and, in turn, resembles the geologists' scheme.

After this adaptation, another version of the diagram was produced by substituting the general terms for others more closely related to the activity. This was done to facilitate the understanding of what students are doing at any given time (e.g. 'select the source of the model' becomes 'interpret the information provided: image and stratigraphic columns'). The outcome represents what we call the referential modelling process for the activity, and is shown in Figure 4.

Therefore, the relationships between the original stages of the MMD (Figure 1) and the corresponding stages in the modelling process required in the activity of 'reconstructing the basin of As Pontes' (Figure 4) that were, in fact, used in the analysis, can be expressed as follows:

Stage 1. It consists of a series of steps that contribute to the development of a mental model of what the sedimentary basin of As Pontes is like, based on students' prior knowledge of sedimentary basins and stratigraphic principles (superposition of the strata and lateral continuity). As already mentioned, it is not possible to access the mental model of each individual, so we use their expressed models to understand how they interpreted the information provided about the basin. However, although we cannot directly analyse their mental models, they were continuously used to interpret the information in the problem and to build a new model of sedimentary basin – aspects that contribute to the students' learning (Morrison & Morgan, 1999). Thus, we build our data from the way they interpret the information (stage 1) and externalise it in the 'expressed model' (stage 2).

The *interpretation of the information* is one of the most important steps of modelling in this context because it requires students to apply their mental models to develop the material model. Two sources of information were provided to the students: (a) the

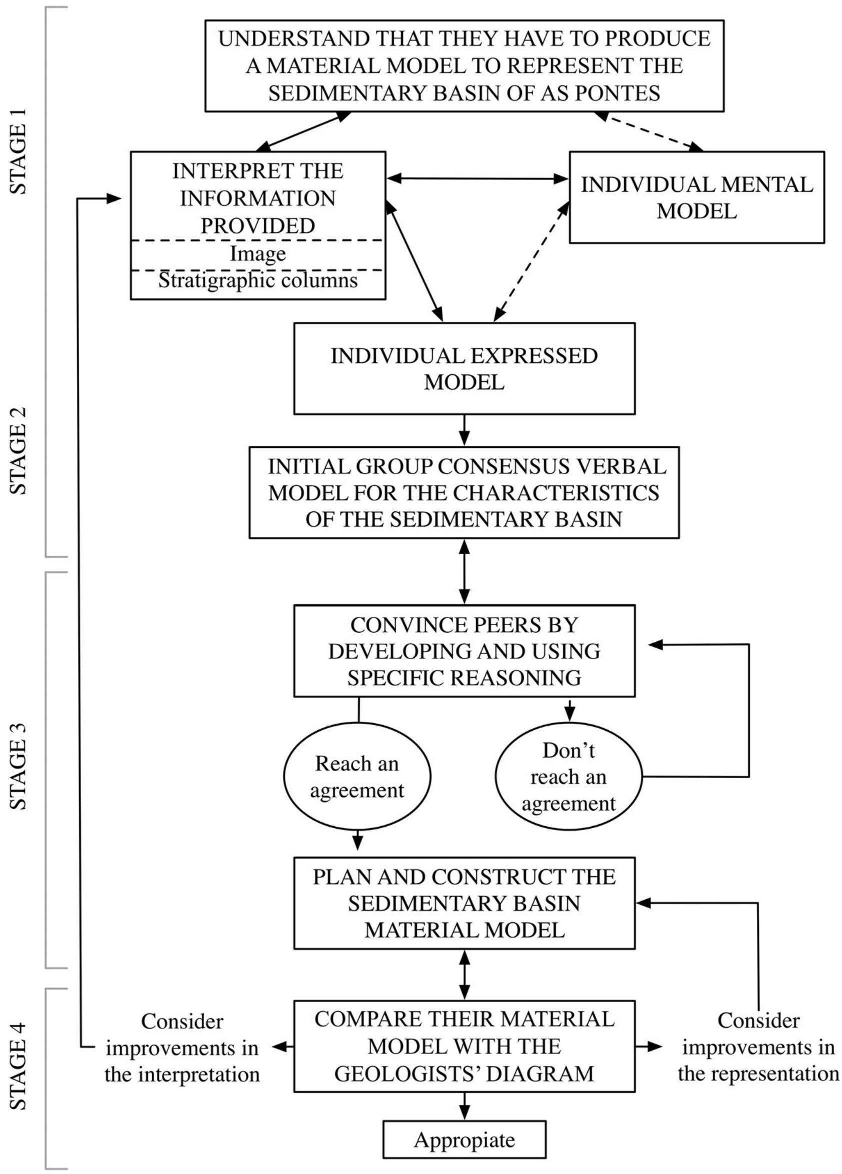

Figure 4. Referential modelling process for the activity 'Reconstructing the sedimentary basin of As Pontes'. Solid lines: explicit relationships. Dotted lines: implicit relationships.

current satellite image of the lake in two dimensions, which was formed as a recovery plan for the mine; and (b) the three stratigraphic columns of the sedimentary basin, taken from the geological survey by Barsó et al. (2003), which provide the third dimension. From the information obtained from those sources, students could produce a mental picture of the basin in three dimensions before constructing the material model.

Stage 2. As seen in Figure 4, the next stage is based on the individual expression of the model and is highly related to stage 1. Therefore, they are placed together under the same bracket. This stage involves students *saying what the characteristics of the sedimentary* *basin are*, and, in order to do so, they have to consider their preliminary interpretations. The outcome of stage 2 is an initial group consensus verbal model.

Stage 3. This includes the interventions in which students try to *convince peers by developing and using specific reasoning* on how to develop the material model. At that time, they have to use the evidence obtained from the information provided to justify their decisions. Once the members of the group have reached a consensus, they proceed to the *planning*, that is, they say how they will use the materials provided, associating them with the strata that appear in the legend, and proceeding with the *construction* of the material model. Thus, it is clear that the testing stage is essential for the modification of the original consensus model and the expression of the resulting model in another mode of representation.

Stage 4. The final stage involves the evaluation of the material model itself, considering whether (a) it meets the characteristics of the 'initial group consensus verbal model' and (b) it is similar to a diagram of the sedimentary basin of As Pontes made by the geologists Barsó et al. (2003). The students themselves determine whether their material model is as expected or has any limitation. In our opinion, the limitations of their models could have been related to: the interpretation of the information provided (formation of the base, number of strata and their power) and the construction of the material model itself, that is, problems when using the materials they were given (for instance, the clay), or other problems, for example, the sand slips between gravels.

The analysis of the modelling processes

After commenting on how the adaptation to the MMD has taken place, we now look at the application of this tool in the analysis of two participating groups: B and J. The diagrams produced for each group show arrows only for the stages observed in that group. In addition, the numbers associated with the arrows indicate the order of the transitions between stages. Those groups were selected because their data are complementary in terms of supporting the discussion of relevant points concerning the adaptation of the MMD.

Group B

The modelling process carried out by group B (Figure 5) shows that the students have understood the objective of the task. Such a conclusion was reached based on the way they performed it, although at no time they had made it explicit. Thus, there is no arrow indicating the relationship between 'understand that they are going to develop the model of the sedimentary basin of As Pontes' and other steps. Those students started the activity relating the materials provided with the strata that appear in the legend (Figure 5, arrows 1 and 3), which corresponds to stage 3 of the process. They decided to choose the materials to represent each stratum because the teacher had insisted that they should do so at that time. Accordingly, they use the criterion of colour as far as possible, since in the case of sandstones they have no choice but to represent them with gravel, as well as the granulometry:

Bruno	t.45	*Shall we place the soil second? It's very thin.*
Benxamín	t.46	*It is very thin. We have to put the sandstone in the middle.*
Bruno	t.55	*Look, this* [soil] *is the coal. Put the coal.*

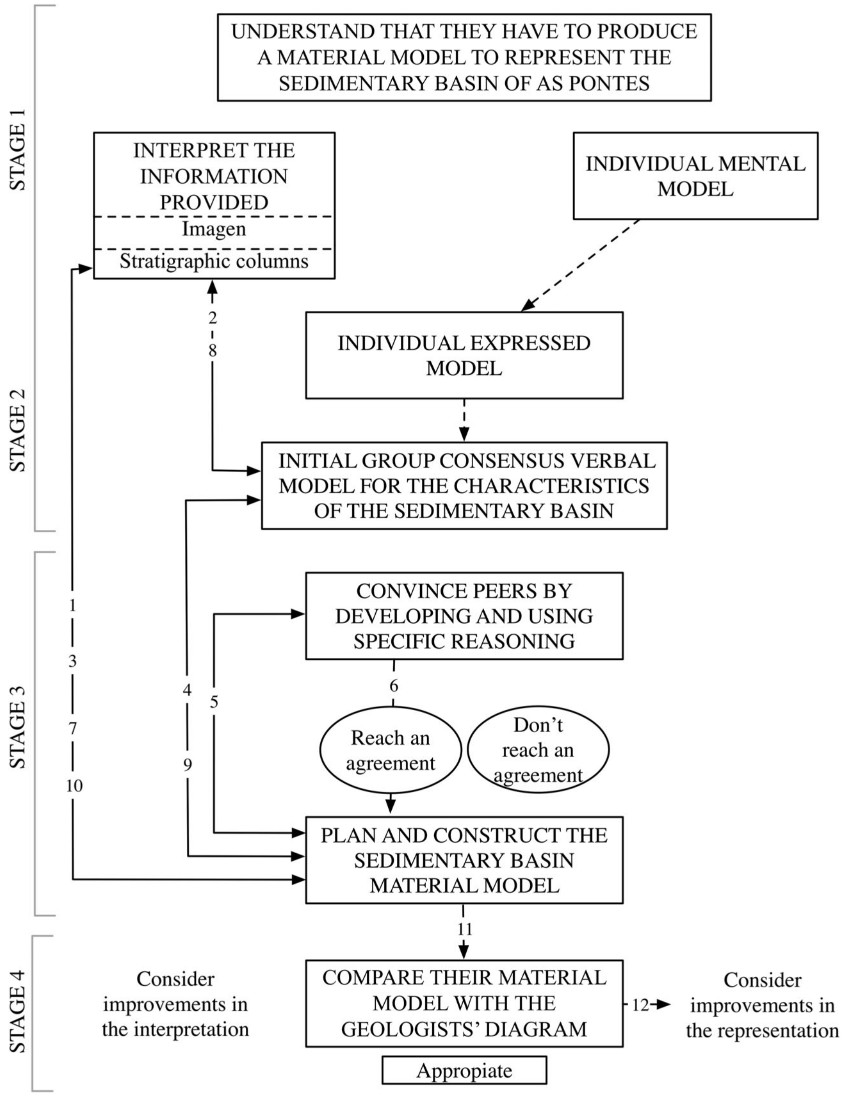

Figure 5. Modelling process of group B for the activity 'Reconstructing the sedimentary basin of As Pontes'. Dotted lines: implicit relationships. Numbers (1–12): order of transitions between stages (1–4).

As mentioned, this would belong to stage 3 of the modelling process, which involves planning the material model, but at that time the students had not yet developed an expressed model of the basin.

Therefore, when they have chosen the materials, they started to interpret the information provided (Figure 5, stage 1, arrow 1), that is, they returned to where they left off, since they had to develop their initial consensus verbal model before the material model. To do this, they expressed the characteristics of the basin following the information of the stratigraphic columns (Figure 5, arrow 2). This group constructed the model as they interpret the information (Figure 5, arrow 3) and reached an agreement on how to represent it (Figure 5, arrows 4–6). This shows the close interactivity between stages 1 and

2, in which the group model is created and expressed simultaneously. First, they carefully represented the base, by taking into account the raised central area, which allowed them to represent the second column:

Bruno	t.67	*And we're going to do it like that? Directly? Well, we need to realise that this part here goes up* [referring to the base of the sedimentary basin]
Breixo	t.68	*Hey!*
Benxamín	t.69	*Put it like that.*
Bruno	t.70	*No, just so we have it clear, this has to go up* [the base] *because it goes up here* [in the drawing]
Benxamín	t.71	*That has to be thin, eh!* [to Bieito, who is shaping the clay]. *It has to be in proportion.*
Bruno	t.72	[Benxamín fits the base] *But you need to make it higher!*

The detailed analysis they (especially Benxamín) made of the columns shows how good have been their interpretation of the data. This leads us to infer that Benxamín had an adequate mental model of what a sedimentary basin is.

Once they have designed and positioned the base, according to the information they have, they began to add the strata. In this group, modelling stages 2 and 3 were closely linked because as one student interpreted the stratigraphic columns and expressed the characteristics of the basin, the others started to develop the material model (Figure 5, arrows 7–10). Moreover, these roles change throughout the task. This made the careful expression of the characteristics of the basin (stage 2) necessary to them, so that they could understand each other.

Benxamín	t.22	*There is no sand on this side … Bieito, mate, you're asleep!*
Breixo	t.23	*Sand! The sand is white, it is everywhere. Look, fill this gap, and around here … And you need to put some mudstone.*
Benxamín	t.24	*Less shale, just put some here.*

One interesting feature of this group is the fact that they use the terminology presented in the activity instead of the common names of the analogue materials they were using. This means that they were appropriating the model of the basin. They also stood out because of the care they put into preparing the material model, especially trying to make sure the sedimentation stages are at the same height, that is, respecting the principle of lateral continuity, and that the strength of the strata corresponds to that which appears in the stratigraphic columns.

Bieito	t.101	*Now, if we level off the coal, which we have on the same line … a bit less in the middle.*
Benxamín	t.107	*Everywhere, until its level.*
Breixo	t.108	*A small layer of coal everywhere.*

Figure 6. The material model built by group B.

Finally, when evaluating their material model (Figure 6) by comparing it with the geologists' diagram (Figure 5, stage 4, arrow 11), they realised that they had not sufficiently highlighted the characteristics they had defined for the basin, which means that their model did not look like it should do (Figure 5, arrow 12). As a result, Breixo (t.141) said '*it doesn't look the same, not at all*', although Benxamín (t.151) was more optimistic when affirming that '*the horizontality of the strata is similar to that of our model*'. Therefore, it seems that the main difficulty experienced by students from group B were related to their limited capacity of handling the materials, since their interpretation of the information was quite correct during the development of the task.

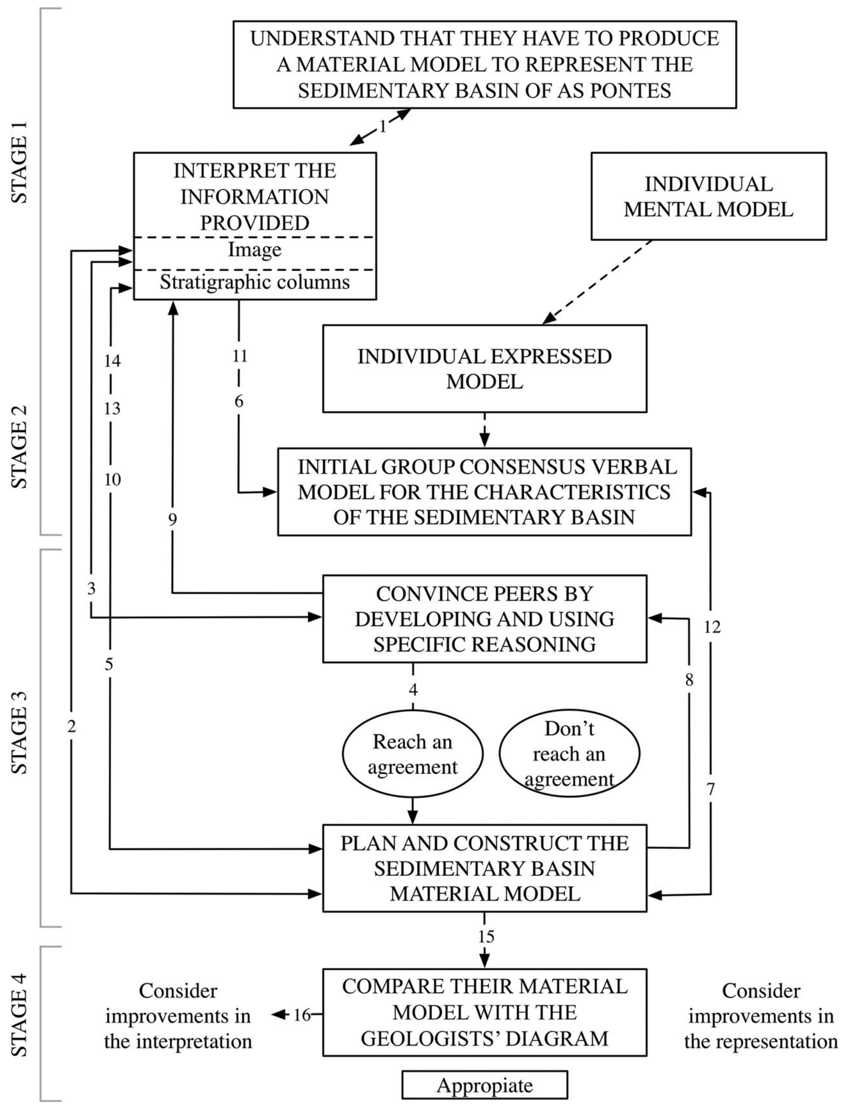

Figure 7. Group J modelling process for the activity reconstruct the former basin of As Pontes. Dotted lines: implicit relationships. Numbers (1–16): order of transitions between stages (1–4).

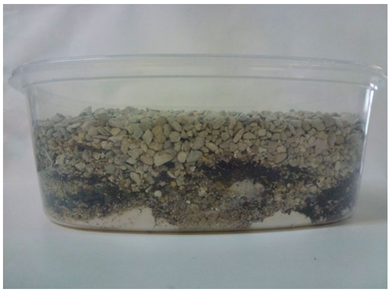

Figure 8. The material model produced by group J.

Group J

In the case of group J, the students have begun the modelling process (Figure 8) identifying the purpose of the problem according to the information available (Figure 8, stage 1, arrow 1). Then, Juana (t.46) said '*we have to build this* [stratigraphic columns]' but Jacinta (t.47) completed the idea, adding that '*what we have to do is take these strata* [stratigraphic columns] *and put them like that* [aerial view]' such that they relate both types of information available.

As it happened in the case of group B, in the next stage the students focused on assigning materials to the strata (Figure 7, stage 3, arrow 2), following the teacher's instructions. Those students were sure about the fact that the soil would represent the 'coal', the beach sand would be used for 'sandstone', and the gravel for 'shale'. However, a small debate on how to represent the base took place. On the one hand, Jacinta insisted that the base should be represented with coarse sand, while Juana expressed doubts about this because the teacher had suggested that the base had to be done with clay. The problem was that Juana had no evidence to confirm her idea, and Jacinta was absolutely sure that they had to use sand because '*we want to do that* [makes waves with her hand]', thus managing to convince her peers (Figure 7, arrows 3 and 4).

Despite this discussion, when they started building the material model, they realised that they cannot model the base with sand and then agreed with Juana's previous idea. At that time, Juana (t.108) expressed her convincing reasoning: '*Of course, that's why I think this* [clay] *should be underneath everything, so we can model it*.' So, according to the relationship established between the materials and the strata, the beach sand would correspond to the 'sandstone', the thick sand to the 'mudstone', the soil to the 'coal', the gravel to the 'shale' and the clay to the 'Precambrian base'.

Once agreed on how to use the materials, they decided to start building the material model (stage 3) while interpreting the information provided (Figure 7, stage 1, arrow 5). Initially, they interpreted the stratigraphic columns (stage 1) while handling it, thus shaping the base. Jacinta was responsible for shaping the base, but her peers were unhappy with her work and asked her to make the base thicker in the centre:

Juana	t.146	*It can't be that flat …*
Josefa	t.147	*No, because there it has to be thicker.*

They found it difficult to make Jacinta understand what the shape of the base had to be, but they finally convinced her and divided the sedimentary basin into three sub-basins (Figure 8, arrows 6–10):

Jacinta	t.174	*Well, but then it needs to be thicker.*
Josefa	t.175	*Of course, there, in the middle, we need to separate it! Here, use this* [she gives her a pen and Jacinta divides it up] *like that. You see … we know what we're doing, don't we? Juana! Now this* [she gives pieces to Jacinta for her to make the divisions]

Once they manage to solve this problem, they realised that the middle of the raised area had to be a small basin. So, Juana (t.243) indicated the characteristics of the basin (Figure 7, stage 2, arrows 11 and 12) '*you have to see a V*', referring to how it should look from the outside of the container.

With the base ready, they started planning how to deposit the materials to represent the strata (Figure 7, arrows 13 and 14). They had two alternatives: to make the sub-basins separately or to add the strata in the three sub-basins when it became necessary:

Juana	t.283	*I suggested making one end not so full.*
Jacinta	t.284	*Ok, do the one in the middle then.*
Josefa	t.285	*I think it's better to do both at the same time.*
Jacinta	t.286	*I also think so, because then it won't take so long.*

When building the material model, they began to deposit the strata in the order indicated in the stratigraphic columns. The greatest difficulties these students have encountered were related to shaping the base in order to represent the three stratigraphic columns. In fact, they made the raised central section of the base with only a little uplift, which later caused problems when trying to match the strata in the three columns. They spent a lot of time adding the materials because they dealt carefully with the order and the strength, thus making sure that it reached the edges.

When evaluating their own material model (Figure 8), compared with that of the geologists (Figure 7, stage 4, arrow 15), they were aware only of the positive coincidences and ignored possible improvements:

Josefa	t.221	*The first stratigraphic column is the same … it's the same! Except for the third column. Look, this* [points to the first part of the diagram] *would be the first stratigraphic column, this is the same* [points to the 1st column on the photocopy] *and the second one too; it has the curve.*
Jacinta	t.222	*The curve goes down not up.*

This group's material model was somewhat imprecise due to problems in the interpretation of the information (Figure 7, arrow 16), that is, due to their misunderstanding of the shape of the base.

Contribution of the MMD to a more comprehensive understanding of the modelling process

Conducting this analysis has given us details about which aspects require special attention when implementing a modelling-based activity in small groups. The main ones are:

The design of the task. As mentioned, the task used in this study was not designed by taken into account the guidelines of the MMD, although it has considered the characteristics of MBT discussed by one of its authors (Justi, 2006). As a result, one issue to be considered is that, after the analysis, it was found that some of the instructions were not necessary. For instance, students were asked to 'Write what you are going to use each material for and the parameters (strata thickness and number of strata …) you plan to

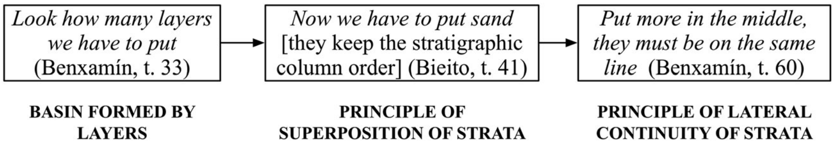

Figure 9. Succession of ideas encompassed in the sedimentary basin model of group B.

represent'. After the analysis, we concluded that this instruction influenced the modelling process, since students spent a considerable time responding it, which was not a priority for the modelling itself.

The teacher's performance. Because the activity was carried out in a regular class, the researchers did not participate in the teaching process. Additionally, although the activity, as well as some ideas on modelling, had been previously discussed with the teacher, he applied it according to what he thought to be the best way to do so. For instance, he asked the students to begin the task by deciding what material they were going to use for representing each sediment. Such an influence became clear when we analysed the data and noticed that, after doing that, the students returned to stage 1, that is, they started to discuss their individual mental models in order to produce the group consensus model, bearing in mind aspects related to the representation codes that would be used in the expression of the group model (stage 3). This situation emphasises the need of modelling training for teachers involved in this kind of activities (as claimed by Bennett, Hogarth, Lubben, Campbell, & Robinson, 2010; Gilbert & Justi, 2016; Maia & Justi, 2009, among others).

Evolution of the models. The use of the adapted MMD as an analytical tool has revealed how students activated ideas related to the sedimentary basin while making the model, as shown in the succession of ideas of group B in Figure 9. At the beginning, they produced a highly fractional model in which only a stratigraphic principle was used. Then, it was changed to a more complete model with several stratigraphic principles to represent the three-dimensional shape of the sedimentary basin. This finding enriches the literature about the group modelling effects on improving students' understanding of scientific knowledge, as reported by Oliveira and Sadler (2008) and Bennett et al. (2010).

Modelling in groups. The analysis of how students generated, expressed and changed their ideas when participating in a modelling-based activity takes on another dimension when it is assumed that students work collaboratively in groups. Our analysis showed that the way and speed with which each member expressed their model kept the ideas expressed by their peers under constant review and modification. In other words, there was a continuous evaluation or confrontation of ideas, which made the stage 'convince by developing and using specific reasoning' a key step in the development of the material model. That is to say, the argumentative interactions promoted in small groups supported the occurrence of a dynamic modelling (Lee, Kang, & Kim, 2015). This was clearly evidenced in the J group, whose members have a good level of knowledge on the subject, which helps them convince their colleagues. This can be exemplified by Josefa's participation when she interpreted the information of the stratigraphic columns: '*but Jacinta, can't you see you have to put more here? Can't you see it's thicker?!*' (t.171).[1]

Conclusions and educational implications

The challenges of using the MMD in this study can be summarised, following our research questions (RQ), in two points: the adaptation of the MMD to modelling in groups and the requirements of the activity (RQ1), and its application as an analytical tool (RQ2).

The adaptation of the MMD concerning to modelling in groups has proved a difficult task mainly because we would like to ensure that the components of the stages of the original diagram proposed by Justi and Gilbert (2002) were reliably maintained. The first challenge concerning the adaptation consisted of characterising the modelling stages carried out by the groups. In order to do so, we had to subdivide the stage 'development of a mental model' to include the two levels: individual and group ones. Accordingly, it was considered that individuals 'create their mental models' and 'express their models' to the group. At the same time, the group's 'initial consensus model' is developed and verbally expressed. Thus, individual mental models are expressed and one model with which all members agree is built. Additionally, we consider that the participation in the group modelling also contributes to the production and/or modification of the individual's mental models through interaction with the ideas of their peers and with the information provided in the task, an aspect that has been previously discussed by Lee et al. (2015). However, due to the impossibility of having access to data that could support such contributions, their influences are not shown in the diagram explicitly.

The second challenge concerned the modification of the testing stage ('conducting thought experiments' and 'designing and perform empirical tests'). Due to the nature of the task, that is, to the fact that thought experiments were carried out by proposing hypotheses on how the materials would be deposited in the basin, that stage implied in the need of convincing peers about which planning was the most suitable. This reinforces the importance of collaborative group in which processes such as persuasive reasoning and justifications take place (Lee et al., 2015; Mendonça & Justi, 2013). Therefore, we had to explicitly include the convincing sub-stage in the adapted MMD (Figure 4).

As for the challenges involved in using the adapted MMD as an analytical tool (RQ2), we highlight three of them. The first, which is intrinsic to the process, is related to the fact that the mental models of each student cannot be accessed (Johnson-Laird, 1983), which means that they cannot be represent in the MMD. This implies that part of the diagram that characterises the whole group process is always detached from the rest of the diagram. In order to emphasise that each student use his/her mental model, we chose to mark the relationships between individual models and other elements of the diagram with dotted lines.

The second challenge is related to the difficulty in analysing the movement of students' ideas in some of the stages of the modelling process. For example, in stages 1 and 2, did the students reach an 'initial group consensus verbal model' or have they 'adopted the expressed model of a peer'? Concerning this dilemma, Mendonça and Justi (2011) discuss that, in the production of a group consensus model, the models expressed by each member merge together, although sometimes the consensus model is very close to the model of one of the members. Consequently, the choice of the model agreed by the students depends on both the options available and the criteria they use to choose among them. This could lead to a 'capture' of ideas that come together in a consensus model (Hewson & Beeth, 1995). However, when collecting data in regular teaching contexts, it seems difficult to clearly characterise this specific movement of students' ideas.

The third challenge relates to the sequencing of the stages of the MMD throughout the discourse of each group. In order to do so, the transcripts had to be carefully sequenced, and the one who transcribed the video had to pay close attention in order to try to identify the intention with which each student had expressed an idea. However, as the analyses of groups B and J show, some actions (sometimes related to distinct stages of modelling) occur simultaneously. This emphasises that the modelling process is highly dynamic and that the attempt to define stages is an option to reduce the limitations of the representation of the process (which, otherwise, would be extremely complex). Therefore, although recognising that there are no clear limits between the modelling stages, it seems worthwhile to analyse the students' actions and ideas that seem to characterise such stages since the outcomes may evidence the complexity of the construction of knowledge through MBT. The interactivity between modelling stages is also clearly emphasised by Gilbert and Justi (2016), when they propose to use a tetrahedron to represent modelling.

After analysing the modelling processes of each group, we concluded that the adapted MMD is well suited to analyse the task insofar, as it allows us to include all the steps taken by students when carrying it out. For instance, although our analysis shows that students did not usually make the purpose of the task explicit, stage 1 could be represented in the figures because their actions showed that they had understood it from the activity instruction. The analysis of the whole process also shows that, in some cases, one of the elements of the process was entirely completed only after the performance of the whole process. For instance, the stage 'interpret the information provided' was essential for developing the model. However, we identified that some students were not able to apply scientific knowledge related to stratigraphy in the production of an initial model. It was during the production and test of the group consensus model that some students showed to have improved their knowledge. That aspect can be represented in the diagram through the double arrows.

In stage 2, students must make their mental model explicit, but this transformation of the mental into the expressed model involves a complex process in which they have to articulate their own knowledge to understand what they know about stratigraphy, what the activity is asking them to do with such knowledge, and the resources available to express their model. This corroborates the idea of García-Rodeja Gayoso and Lima de Oliveira (2012) whereby explanatory models are generative and, therefore, evolve as the student acquires knowledge.

Our data show that stage 3 was the most complicated for the students because it required justifications to convince their peers. Although sometimes there were no reasons to argue (either because the students agreed with their peers' ideas, they had the same view, or because they preferred to adopt the proposals of their peers), other times they really had to argue in order to persuade them that a given idea was better than another one. This is consistent with Bennett et al. (2010) who have founded that group dissimilarity in opinions contributes to increment understanding. Nevertheless, we consider this stage one of the most important in modelling-based learning because if the individuals do not discuss their models, they will not have the opportunity to revise or learn from it (Morrison & Morgan, 1999).

Finally, in stage 4, students from group B showed a more critical attitude of its material model by appreciating the improbable aspects and highlighting the characteristics that their material model shared with the geologists' one. However, this critical attitude was missing in group J, whose students showed a complacent attitude toward their material model. This leads us to consider that the teacher has to emphasise to students the value of identifying the limitations of their models (Gilbert & Justi, 2016) in order to apply them in suitable contexts.

From the results of our study, we agree with Justi (2006) that modelling is a teaching strategy with potential for supporting students to do science and to think about science. As models include tacit knowledge, that is, knowledge we are not aware we have, it may be expected that students could become aware of both the knowledge they have and their shortcomings. Moreover, by using their own models, students may organise their knowledge to facilitate its application in solving other problems (Nersessian, 2002).

One of the main advantages of the MMD (Justi & Gilbert, 2002) is to focus on the essential elements of modelling, thus having an open and flexible structure that facilitates adaptation to any modelling context. On the other hand, our adapted MMD makes it possible to characterise the process as it happens when performed collaboratively in a group of students. As in regular educational contexts students usually work in groups, the use of the adapted MMD becomes essential in order to support our understanding of students learning process in MBT contexts.

Concerning RQ3, in our view, the type of analysis we performed in this study improves our knowledge about the interactions between students' ideas, new information, and their new models, as well as about how they affect students' learning. In the recent years, students have been increasingly asked to work in small groups, especially when they participate in teaching activities based on scientific practices that require collaborative work (Oliveira & Sadler, 2008). Our analysis shows that to involve students in modelling activities in groups may help them to share their doubts and negotiate their ideas (as previously discussed by Mendonça & Justi, 2011), and to express their models using various modes of representation, thus learning about the value of each of these modes. As most of the authors who study MBT have previously emphasised, this teaching approach requires more time than traditional teaching methods. On the other hand, studies like the current one show that it is highly likely that modelling activities encourage students to consider the existence of different models, which allows them to generate richer and more complex explanations.

Finally, we are aware that there are many other issues to be investigated concerning students working in groups when carrying out modelling activities. Future studies could be focused on investigating, for instance, (a) the extent to which each member participates in the development of the model, (b) how the model expressed by one student affects the model expressed by other members of the group and (c) if, and how, a given student deal with his/her prior individual model and the group consensus model when he/she has to use them in distinct contexts. Due to their nature, it does not seem that such investigations could be conducted in regular classes. Notwithstanding, they may contribute to improve our understanding of how students engage in modelling activities and how specific activities may support the construction of knowledge in the context of MBT. Both issues are very important to support the proposition of guidelines for teachers' actions when planning and conducting modelling activities.

Note

1. Although we recognise the importance of the occurrence of such argumentative interactions, we do not detail them here because this is out of the scope of this paper.

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Appendix

Reconstructing the sedimentary basin of As Pontes

In As Pontes Garcia Rodriguez, a municipality in the district of Eume, there is a power station that runs on coal. Until a few years ago, the coal was extracted from a sedimentary basin close to the power station.

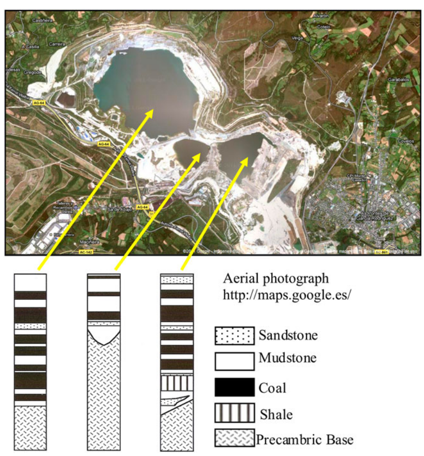

Figure A1. Stratigraphic sections of the sedimentary basin.

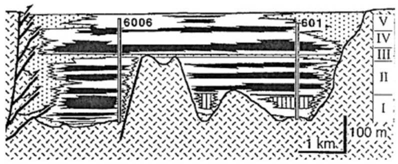

Figure A2. Diagram of the stratigraphic basin taken from Barsó et al. (2003)?

The following are three stratigraphic columns, dating from before the coal was mined. Each of them corresponds to one part of the basin. The aerial photograph shows the basin under reconstruction, i.e. the formation of a lake.

With the information provided, you have to reconstruct the sedimentary basin as it was before the coal was mined for the power station.

Write down which materials you are going to use for specific purposes, and the parameters (strata thickness, number of strata...) you plan to represent.

Material available: modelling clay; soil; gravel; beach sand; coarse sand; transparent plastic container.

When you have finished the model, answer the following questions:

a) How many sedimentation stages are there? Which aspects have you used to base your answer on?
b) Which stratigraphic principles did you use to build the model?

Then observe the diagram of the stratigraphic basin made by the geologists
What similarities and differences do you find between your model and their diagram?