COGNITIVE PROCESSES ENACTED BY LEARNERS DURING CO-CONSTRUCTION OF SCIENTIFIC MODELS

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Abstract

The study documents on our effort to analyse students' cognitive processes during modeling-based learning. A modeling-based teaching intervention was developed and implemented during a summer science class at the University of Cyprus (n=17). Students worked in small groups to develop successive models of simple systems in the topic of heat and temperature through the use of DynaLearn modeling tool. Students' conversations were videotaped and transcribed in the Transana software. Additionally, students' work and conversations were analysed with a combination of two techniques; a video analysis framework which considers class work in terms of three different scales (macro-, meso-, micro- scale) and a coding scheme for students' cognitive process during modeling. This paper presents the work of two groups of students. Results indicate differences and similarities of the work and the cognitive processes of the two groups at the three scales of analysis. We discuss those differences and similarities under the spectrum of their importance to science education.

Keywords: Modeling competence, cognitive processes, modeling-based learning

1. Introduction

Learning by constructing models denotes the process through which learners construct and use scientific models aiming at the construction of explanations about complex systems or natural phenomena [1]. Through modeling learners are engaged in the processes used by scientists, who construct and use models in their everyday activities [2, 3]. Additionally, they gain understanding about how knowledge is constructed as well as about the nature of science. Modeling competence comprises of modeling practices in which learners are engaged (i.e. model construction, model use, model comparison, model evaluation and revision, and model validation) and metaknowledge, which includes metacognitive knowledge about the modeling process and epistemological awareness about the nature and the role of models and modeling [4, 5]. When engaged in modeling practices, specific cognitive processes (analysis, explanations, quantification, inductive reasoning, evaluation and revision) are enacted by the learners [6]. The outcome of the modeling process is an artifact, here constructed by the learners, the scientific model. A scientific model is a set of systematic representations of a system or a phenomenon, which provide a mechanism about the function of it and allows for making predictions about the future evolution of the phenomenon [5, 7].

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As a process of engaging learners in (co)constructing scientific models to gain understanding about natural phenomena, modeling is intrinsically related to the constructivist approach to teaching and learning, and more specifically to constructionism, which is based on the idea that learners, through the use of the appropriate tools, construct their knowledge through building artifacts, here models [9, 10]

Given the aforementioned advantages of modeling-based learning, the need to empower teaching interventions aimed at developing the modeling competence is emerging, and hence the need to establish methods for analyzing and assessing the ability of learners to develop and deploy models. This is especially important if teachers are expected to introduce learning by modeling in their teaching practice. The present research aims to that direction. Specifically it sets out to address the following research question: "Which cognitive processes are enacted when learners co-construct scientific models? How is the work of two different groups compared?"

2. Methodology

2.1. Participants:

The study involved 17 high-school learners (5 girls and 12 boys, 15-17 year olds) who attended a summer science class at the University of Cyprus. Learners worked in small groups (5 groups of 3 and 1 group of 2 learners). The intervention was completed in 7 lessons and the total duration was 7X90minutes. Two groups of learners were randomly selected for analysis presented in this paper. Both groups consisted of two boys and one girl.

2.2. Intervention

The overall course structure was formulated as an iterative procedure, which involved the learners in an active and collaborative process of co-constructing and deploying successive models within their group, among groups in class (Face to Face), and through the internet (Stochasmos Learning Platform[2]). The modeling procedure was scaffolded by the use of two forms for communication purposes. Each group of learners (e.g. group 1): (1) Constructed a model and filled in a model coding form. In the model coding form each group (e.g. group 1) reported information about the basic features of its model (model 1 of group 1). This form was communicated by the modelers (e.g. group 1) to other users of the model (e.g. rest of the groups). (2) Assessed a model of another group (e.g. groups 2) and filled in a model assessment form. In the model assessment form, each group (e.g. group 1) provided feedback about the model of another group (e.g. model 1 of group 2) about the basic features of the model. Each group (e.g. group 2) then used this feedback to improve its model. This form included assessment points provided by the evaluator of the model (e.g. group 1) to the group that constructed the model (e.g. group 2). Both the forms and the group models were uploaded to the Stochasmos Learning Platform which included a file-sharing feature and which helped groups in the model exchange process. All groups had the opportunity to download the artifacts of any group in the class.

Each group developed two successive models about simple systems of heat and temperature. The construction of the two models was based on two different set of provided data. The first set of data concerned the thermal interaction of two bodies with the same mass and different initial temperature and the second set of data derived from experiments of thermal interaction of bodies with different

[2] www.stochasmos.org/

mass and initial temperatures. The main structure of the course is summarized through the macroscopic analysis presented in the results section.

2.3. Modeling tool: DynaLearn

Learners used the DynaLearn Interactive Learning Environment [8] which enables them to create conceptual models by working through several stages of representation (Learning Spaces) from specifying and interpreting simple, static concept maps at the lowest level (level 1), to complex dynamic models with advanced representations for capturing causality at the highest level (level 6). The learners reported on in this study used Learning Space 4. This modeling tool allows the user to construct conceptual models (here about simple systems of heat and temperature) which include entities, properties of these entities as well as assign relationships (causal) to those properties. The user can also simulate the model and attain, in the form of stategraphs, the progress of the phenomenon.

To illustrate this class of models consider the details shown in Figure 1, which describes a model developed in DynaLearn by a group of learners. This model included three entities, notably First cube, Medium and Second cube. Both cubes are assigned the quantity Temperature and Heat. The current value for Flow is unknown, as is its direction of change (∂). The following dependencies hold. The magnitude of Flow is determined by the difference between the two Temperatures. The Flow negatively influences (I-) the Heat of the First cube, and positively (I+) the Heat of the Second cube. Changes in these temperatures positively influence (P+) changes in the respective Heat quantities. Changes in these heats then feed back into changes of the Flow, positively from the Heat of the First cube (P+), and negatively from the Heat of the Second cube (P-). Finally, Temperature of the First cube is higher (>) compared to the Temperature of the Second cube, which together with the subtraction of the two temperatures implies that the Flow is above zero (in the value Plus). The software allows for simulating the model. Figure 2 shows the simulation result for the model presented in Figure 1.

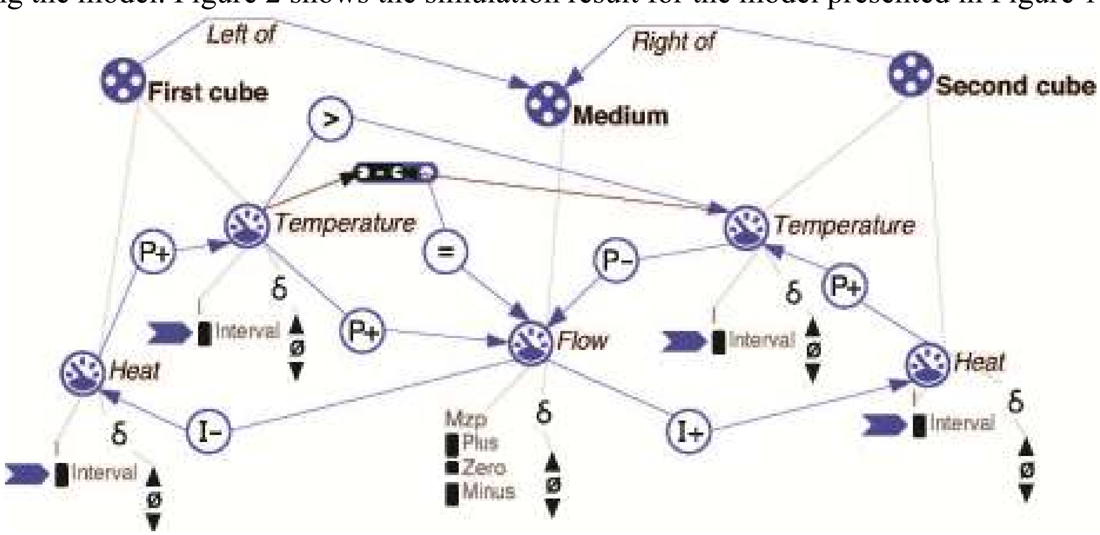

Figure 1. Model of a System of 2 bodies with different temperature and mass built in DynaLearn (Learning Space 4).

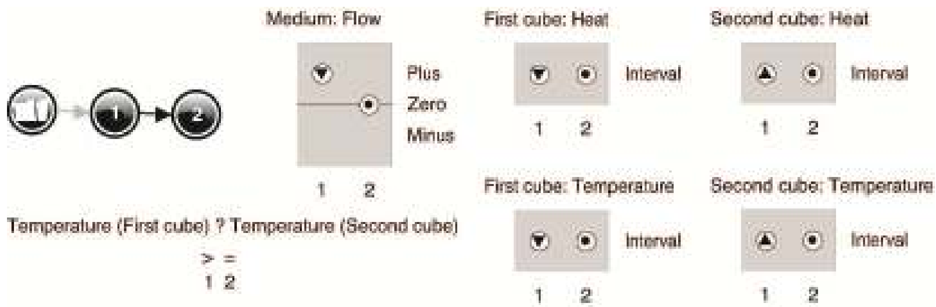

Figure 2. Simulation results of the model of a System of two bodies with different temperature and mass (Figure 1)

2.4. Data collection and analysis

The means of data collection are the videotaped conversations of two groups of learners. The software program Transana, was used for transcribing and analysing learners discussions. Data analysis implemented the framework for analyzing videos as described by Tiberghien and Malkoun [9] which includes analysis at three scales: macro-, meso- and microscopic scale. The *macroscopic analysis* is common for all groups of the course. It captures task flow as it was designed by the teacher. Therefore, no duration is noted. On the other hand, the mesoscopic and the microscopic analysis differ for the two groups as they are based on the actual students' conversations. At the *mesoscopic level* a deeper analysis of the conversations takes place. The conversations are categorized into episodes according to the context, in other words, the "taught knowledge". Each episode is accompanied by its duration and a title, which describes its content [9]. The title of a theme represents the theme content; and it should be as close as possible to the effective discourse. The series of these episodes constitute the mesoscopic analysis, which is a sequence of the different episodes in a chronological order. Analysis of students' conversations at the *microscopic level* is even deeper. At this level, the purpose is to highlight the details of students' conversation. The use of keywords to identify these details is one way to perform this analysis. For the present study, the coding scheme of Sins et al [6] was used. Therefore, the keywords are the cognitive processes as described by these researchers (Table 1) and each episode was divided in snapshots with regards to the identified cognitive process or processes.

During this process, the research team held a number of discussions where consensus was built on the way the data were being interpreted. During these discussions, coding was revised and refined a number of times. Two of the seven lessons were analysed independently by two researchers (the first and the third author), and a high degree of agreement was achieved (83%); discrepancies were resolved through discussion of the particular cases. The remaining data were categorized by the first author.

Cognitive process	Example
Analyze: Learners talk about/interpret modeling elements. They identify factors that may be relevant or not to their model. They identify elements of the phenomenon that should be included in their model.	*St17[3]: Let's start with the basic elements of the model* *St13: Hot and cold cube.* *St17: Shall I put something like "flow"?* *St15: Relations…those….contact? (..)* *St17: Heat and flow are the properties! (..)* *St15: Temperature transfer is a process! (..)* *St17: We didn't include mass as a property of the cube…* *St15: …we need to put mass.*

[3] St=learner, T=Teacher

	[Group 1, lesson 4, episode 07,"analyse", model 1(basic)]
Quantify: Learners talk about quantifying or specifying a relationship within their model. When they construct a preliminary model, they can make their ideas about model elements and relations more precise by expressing them into a mathematical form.	*St17: Mass is five times more, and the change in temperature for this cube is five times more, so this is 1/5 of the temperature.* *St15: Didn't we say that it is 8 times more?* *St17: Yes, this 8 and this 2, so 4 times more. For this experiment, the mass of the hot cube is 4 times more than the mass of the cold cube. And the change of the temperature of the cold cube is four times more than the change of the temperature of the cold cube.(..)* *[Group 1, lesson 6, episode 03,"quantify", model 2 (advanced)]*
Inductive reasoning: Learners elaborate upon elements within or with respect to their model (mainly qualitative reasoning). They express hypotheses on how elements interact and how they behave in their model.	St17: Does the temperature of the hot cube decrease when the flow is positive? Yes! St15: When the flow decreases, temperature increases? St17: Yes! St15: no, no…when the flow increases, its temperature decreases. *[Group 1, lesson 4, episode 07,"quantify", model 1 (basic)]*
Explain: Learners explain to each other how elements within their model work or why they were included (or excluded). Sometimes, explanation is preceded by a clear-cut question of one of the learners.	*St17: So, when temperature decreases, the flow increases, so it is this button (software feature)* *St13: Why this?* *St17: (..) this button (P+) tells us that when the temperature of the hot cube decreases, the flow increases, because temperature is moving from the hot to the cold cube.* *[Group 1, lesson 4, episode 03,"explain", model 1 (basic)]*
Evaluate: Learners compare the data (the phenomenon) and their model. They determine if the model accounts for those data.	*St02: it (the model) doesn't work (..)* *St06: The cold cube's behavior is correct. It is the cold's behavior that is wrong. It is constant.* *T: We don't get equilibrium…* *St06: exactly! This should go up and this down, but they don't!* *[Group 2, (lesson 3, episode 07,"evaluate", model 1 (basic)]*

Table 1. Description of cognitive processes[4]

3. Results

3.1. Macroscopic Analysis

Table 2 shows the macroscopic analysis of the study and therefore the overview of the course, which is common for the two groups of students, the work of which is analysed in this paper. This analysis shapes the two modeling-based cycles implemented in the course which resulted in the two successive models for each group (basic and advanced). The basic model resulted from the implementation of the first modeling-based cycle and concerned the first set of data and the advanced model emerged as a need to account for the new set of data as well as a need to address the evaluation provided by peers through the model assessment form.

Data set1: Study of existing data which resulted from a set of experiments where different bodies of different temperature and the same mass contact each other
Basic model: Construction of a model to account for the patterns identified in the data of the first set of experiments
Peer-Assessment: -Fill in the model coding form for the basic model -Assess the basic model of another group -Fill in the model assessment form for the basic model of other group.
Meta-knowledge of modeling: -Discussion about the nature and the role of models and modeling. -Each group presents and share its ideas and knowledge to the rest of the groups -Inter-group discussion about each other's ideas

[4] The categories used for this analysis (first column) are borrowed by the work of Sins and his colleagues (6). The examples provided in this table are from our research.

Data set2: -Study of data which resulted from the second set of experiments where different bodies of different temperature and mass contact each other -Comparison of the basic model and the data
Model revision→advanced model: -Improvement of the basic model to account for (i) the new data and to (i) assessment received through peer-evaluation -Construction of the advanced model
Peer-Assessment: -Fill in the model coding form for the advanced model -Assess the advanced model of another group -Fill in the model assessment form for the advanced model of other group.

Table 2. Macroscopic analysis of the course

3.2. Mesoscopic Analysis

This section presents the summary of the Mesoscopic analysis for the two groups of learners, group 1 and group 2.

Group 1: Learners completed task 1 and 2 in the first lesson and started the third one. Task 3 was done during the second, the third and the forth lesson. During construction of model 1, learners' conversations focused on qualitative relations between temperature and temperature flow. They discussed about these concepts and argued about whether they should include them and their relations in the model. During lesson 4 model 1 (basic) and model coding form were completed and uploaded on the learning platform. Then group 1 downloaded and assessed model 1 of group 2. They also received feedback about their model, which was described in a model assessment form by group 2. They revised their model based on this feedback. Task 4 was completed during the fifth lesson as well as task 5. Task 6 started at the beginning of lesson 6 and was followed by task 7, which included the revision of model 1 that was completed during the last lesson.

Group 2: During the first lesson learners completed task 1 and begun with task 2. In the second lesson they constructed a concept map and completed task 3. Specifically, during the third lesson learners argued about the qualitative relations between the variable quantities of the phenomenon and the model. At the forth lesson, they filled in the model coding form, during which they again discussed around the qualitative relationships between the model's variables. During the same lesson, they assessed the model of another group (basic model of group 1) while at the same time, they received the evaluation about their own model from the other group (group 1). They revised their model based on this assessment. Tasks 4 and 5 were completed in the fifth lesson. They started with task 6 at the sixth lesson. This task prompted learners to discuss about the quantitative relation of mass and temperature. During the seventh and last lesson learners started revising their model based on the assessment provided by the assessor group as well as on the new data. In the frame of these revisions they included heat as a variable quantity in their model. When the model was finished, they evaluated the second model of group 1.

Date 01/07/2013 - Lesson 1: Group 1		
Episode and Title	**Description**	Duration
1. Instructions by the instructor	The instructor introduces the content and the process of the course to the students. Students watch a video about thermal interaction of bodies	0:12:48
2. Task 1, Temperature measurement	Students measure the temperature of objects in the class environment	0:22:01
3. Task 1. Rule1: same environment→ same temperature	Express rule 1: objects in the same environment have the same temperature, besides heat sources	0:20:52

4. Task 2, Data set 1: "Contact of bodies with different temperature and the same mass"	Students elaborate on the given data of the first experiment (two objects of the same mass and different temperatures contact each other) and try to identify patterns out of them	0:01:52
5. Task 2, Rule 2	Students report their conclusions with regards to the data of the first experiment. They write down the second rule: when two objects interact thermally they reach the same temperature.	0:00:33
6. Task 2, concept map "thermal interactions of bodies"	Students build a concept map in the modeling tool (DynaLearn) about the ideas emerged by the two experiments and which concern the thermal interactions of bodies.	0:03:40

Table 3. Example of mesoscopic analysis for group 1

Date 01/07/2013 - Lesson 1: Group 2		
Episode and Title	**Description**	Duration
1. Instructions by the instructor	The instructor introduces the content and the process of the course to the students. Students watch a video about thermal interaction of bodies	0:12:48
2. Task 1, Temperature measurement	Students measure the temperature of objects in the class environment	0:04:54
3. Task 1, Rule 1	Express rule 1: objects change their temperature according to the environment they are in.	0:03:41
4. Task 1: discussion with the instructor about the video	Students discuss with the instructor about their conclusions with regards to the video which guided them to the idea that the hand is not a valid temperature measurement tool	0:02:59
5. Task 1, Temperature measurement	Students repeat the measurement of different objects in the class environment	0:04:30
6. Task 1, Rule 1	Students report a new rule after repeating temperature measurements. Rule 1: objects change their temperature according to the environment they are in. Objects in the same environment have the same temperature	0:04:09
7. Task 2, Data set I- *"Contact of bodies with different temperature and the same mass"*	Students elaborate on the given data of the first experiment (two objects of the same mass and different temperatures contact each other) and try to identify patterns out of them	0:07:32
8. Task 2, Comparison of the provided data with their own measurements	Students discuss with the instructor and try to combine the results of their measurements and the given data of the first set of data.	0:03:56
9. Task 2, Data set 1: pattern: temperature exchange	Students discuss with the instructor and try to identify patters in the given data. They conclude that the objects exchange temperature.	0:05:29
10. Task 2, Rule 2	Students report their conclusions and write down the second rule: when two objects interact thermally they reach the same temperature.	0:06:58

Table 4: Example of mesoscopic analysis for group 2

3.3. Microscopic analysis

Table 5 presents the cognitive processes in which learners of both groups were engaged during modeling with respect to time for all seven lessons (total work time=630 minutes).

Group 1		**Group 2**	
Cognitive Processes	**Duration**	**Cognitive Processes**	**Duration**
Inductive Reasoning	1:03:43.7	Inductive Reasoning	0:41:42.0
Explain	0:58:00.9	Evaluate	0:27:07.0
Evaluate	0:33:23.5	Explain	0:12:00.0
Analyse	0:18:40.4	Analyse	0:09:21.0
Quantify	0:14:46.2	Quantify	0:08:03.0

Table 5. Microscopic analysis for the work of the two groups. groups

The data presented in Table 5 show that students of both groups are engaged in specific cognitive processes in quite a similar order. Inductive reasoning is the most enacted process while analyse and quantify are the less common cognitive processes identified in students conversations for both groups. The only difference between the two groups is the ranking of explaining and evaluating. Explaining was most common for group 1 and less common for group 2 when comparing with the cognitive process of evaluating.

Learners were engaged in a discussion about the qualitative relationships of the phenomenon so as to include them in the model (Inductive Reasoning):

St17: So...if the temperature of the hot cube decreases, the flow increases. So this is the correct sign (...)
St17: The temperature of the hot decreases, so the flow increases. What does this tell us? Wait a minute (he looks in his notes) P+ means that it increases, so it should be vice versa, so…
St13: So it should be that one.
St17: It should be negative
St13: Put negative!
St15: Yes. When this increases…
St17: If this decreases, if the temperature decreases, flow increases
[Group 1, 4/7/2013, Episode 03," inductive reasoning", model 1(basic)]

This conversation imprints students' efforts to construct their first (basic) model by running it on the modeling tool and checking if the phenomenon evolves as expected. They discuss about the analogical relations between the model variables. At the end of this conversation, student 17 concludes that if the temperature of the hot cube decreases the flow from the hot cube decreases.

Explaining, in other words clarifying why model elements are related and how they work, occurred for 58 minutes in group 1 and only 12 minutes in group 2:

St17: The mass of the first cube is fivefold the mass of the second cube, so this is one fifth of the temperature. Here, see. The mass is fivefold….
St15: Isn't it about 8?
St17: Yes. This is 8 and this is 2, so it is four times more…this cube has four times greater mass than this, and the change in the change of temperature for the second cube is quadruplicate the mass of the first one.
St15: Ok, I got it now. Thanks
[Group 1, 8/7/2013 Episode_03, explain, model 2 (advanced)]

Students of group 1 analyse the given data and discuss the analogical relation between mass and temperature. While discussing this relationship, student 15 express wonders whether the mass difference is 8. Then student 17 confirms that this number is the mass difference and explains the relationship between the mass difference and the difference between the temperature change of the two cubes.

Evaluating their models also took much of students' time (33΄ for Group 1 and 27΄ for Group 2):

St06: I think I did it! The temperature of cube b reaches maximum but... (for cube a) is plus.
St02: Yes! But it is not at maximum…
St06: it is..plus
St02: It is not going to reach minimum.
St06: The temperatures should be the same...
St02: It decreased

St06: No it didn't.
St02: From maximum, it went to the plus
St06: Then, why this cube's temperature went to maximum? They should reach the same temperature
[Group 2, 3/7/2013, Episode_04, "evaluate", model 1 (basic)]
This extract includes students' (group 2) effort to assess their first (basic) model. To do so, they run the model several times and checked the simulation results, which they evaluate and compare to the real data (given experimental results). Students 2 and 6 identified a problem with the simulation results as the final temperatures of the two cubes are not the same, they don't reach equilibrium.

Learners of both groups spent less time on analyzing the phenomenon, i.e. identifying the constituent components (objects, variables, processes and relations) of it with an aim to include them in the model. Students of group 1 spent 18 minutes while students of group 2 only 9 minutes in analyzing the phenomenon. An example of this cognitive process is shown in table 1.Finally, it is worth mentioning that the cognitive process of quantifying was present only three times during the whole course for group 1 and four times for group 2. This discussion concerned (a) the relationship of the temperature of the cubes and the heat flow for the basic model (model 1), and (b) the relationship between the heat transferred from and to the two objects and the heat flow for the advanced model (model 2). An example of this cognitive process is shown in table 1.

4. Discussion

The emerged data composes a way to conceive the whole picture of the teaching and learning process. The video analysis framework by Tiberghien and Malkoun [9] enriched with the coding scheme of Sins et al. [6] revealed the main differences and similarities of the work of the two groups at the three different scales (macro-meso-micro).

At the *macroscopic scale* the teaching sequence was common for both groups, as they were students of the same classroom. At the *mesoscopic scale*, the sequence and the variety of the discussions and the work of the two groups held many commonalities, but, specific differences were also identified. For example, Tables 3 and 4 show that group 1 followed a serial way to attend the requested tasks and seemed to be more effective comparing to group 2. Group 1 was following the curriculum as presented, that is, students reached consensus for each part of the task and then moved forward. In the same period of time (about one hour) students of group 2 revisited a sub-task two times with an aim to solve some discrepancies (points 3 and 6 and points 7 and 9 in table 4). Additionally, they completed less work than group 1. Given the results of the macroscopic analysis one would expect that students of group 2 would be engaged in more deep cognitive processes comparing to students of group 1. The microscopic analysis of the data of the two groups pointed, however, to another direction. Students of group 1 were more engaged since the time they spend on each cognitive process was higher comparing to the time spend by the students of group 2. We consider that the reason behind this discrepancy could be that students of group 1 were talking out all the concerns, problems, arguments or counterarguments at the intragroup level of collaboration (within group), which resulted in a process of collectively solving problems and collaborating to reach the group's goals. On the contrary, learners of group 2 tented to work silently without externalizing their thoughts much. They were working most of the time on the computer and while collaborating, sometimes even through gestures they were not externalizing those conversations. This could be the reason for returning back to their initial decisions, as they were not formed by the group in unison.

Additionally, the findings from the microscopic analysis contradict the results of Sins and his colleagues [6] who concluded that students spend more time in quantifying the relations of their model and less time in inductive reasoning. The results of our research study indicate the contrary, as students of both groups spend their time mostly for identifying or discussing qualitative relationships between model's elements and the least of their time on quantitative relationships. The inconsistency seems to be explained by the different software used in the two studies. DynaLearn, the tool used in the present study, supports the construction of qualitative models in contrast to Powersim, the tool used in the study of Sins and his colleagues supports the construction of quantitative models, therefore the former prompts learners to discuss and think of the qualitative relations of models elements and the latter of the quantitative relations of model's elements. Therefore, it seems that the modeling tool used by learners as a means to construct their models guides their cognitive efforts and could lead to different learning pathways [10].

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