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On analysis of collaborative problem solving: an object-oriented approach

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Abstract

During the last decade an increased interest has been observed on computer-supported collaborative problem solving. This relatively new area of research requires new methodological approaches of interaction and problem solving analysis. Usually analysis of collaborative problem solving situations is done through discourse analysis or interaction analysis, where in the center of attention are the actors involved (students, tutors etc.). An alternative framework, called "Object-oriented Collaboration Analysis Framework (OCAF)" is presented here, according to which the objects of the collaboratively developed solution become the center of attention and are studied as entities that carry their own history. This approach produces a reversed view of the process, according to which the solution is made of structural components that are 'owned' by actors who have contributed in various degrees to their development. OCAF provides both qualitative and quantitative measures of collaboration. It is shown that this framework can be applied effectively both in synchronous computer supported collaborative environments of distance groups and in face-to-face collaborative activities.

Keywords: Collaborative problem solving; Object-oriented approach; Educational software

1. Introduction

Recent socially inspired theories on learning, supported by the growing development of network technology, have resulted in an increase of research on technology-based collaborative learning environments. The issues involved in this research effort

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concern either collaboration of remote groups, or support to collaborating individuals working side by side. In either case the outcomes usually influence our considerations on effectiveness of the collaborative learning process, the designation of appropriate learning activities and settings, as well as the design of collaborative technology-based learning environments. According to all these perspectives, the methodological issues of collaboration analysis are of prime importance, given that they are directly related to the development of this research and technology area and the common understanding of the various disciplines involved.

If we may attempt an overview of research development in this area during the last years, we can distinguish three periods. During the first period, the main objective was to explore effectiveness of collaborative learning, controlling different independent variables (group composition, communication media, task structure, etc.). During a second period, empirical studies have started to focus more to understanding the role of these variables in mediating interaction. So, the methodological analysis was shifted to a more process-oriented approach of the dynamics of collaborative interactions (Dillenbourg et al., 1996). Within this interactionist paradigm, the group itself became the unit of analysis and the usual approach was to study the verbal interactions and to attempt to relate features of them to possible learning effects (Baker & Lund, 1997). More recently, research on collaborative technology-based learning seems to move through a third period during which, by exploiting the previous results, it is now oriented not only to design appropriate systems, activities and settings (Dillenbourg & Traum, 1999), but also to establish effective analysis and evaluation methodologies, pushed by the intensive interest to use collaborative systems in every day educational practice, where there is a need to evaluate in an operational way both learning outcomes and quality of collaboration.

Different kinds of tasks are typically involved in collaborative learning activities, such as working on the *production of a story* (O'Malley et al., 2000), on *argumentation* related to a subject (Suthers, 1999a), etc. One of them, eventually the most eminent, is *problem solving*, taking place in appropriate situations and collaborative learning settings (Dillenbourg, 1999) that permit a mutual engagement of participants in a co-ordinated effort to solve the problem together (Roschelle & Teaslay, 1995). In problem-solving collaborative learning activities the computer-based learning environment constitutes in itself a mediational resource, which can contribute to create a shared referent between the social partners (Roschelle & Teaslay, 1995). Typically these *direct manipulation* environments are characterised by actions on objects representing entities or on concepts meaningful to the users. Usually operations on these objects have a reversible incremental effect on the 'environment' represented on the computer screen. Often more than one actor interact directly or indirectly with the objects in this world modifying their state, communicating between them and through the objects, as they advance problem solution. Analysis of these problem-solving situations is usually done through discourse analysis (Baker, Hansen, Joires, & Traum, 1999), task analysis (Tselios, Avouris, & Kordaki, 2002), communication and interaction analysis, or even a combination of methods, with the objective to evaluate the situation, the learning process and often the tools used. An overview of proposed techniques is included in the following section of the paper. However in these analysis techniques the centre of attention are usually the actors (students, teachers etc.) and the dialogues, while the developed objects enter the scene as items on which operations are effected and as subjects of discussion.

An alternative and complementary framework of analysis is presented here, according to which the objects of the solution, that is the objects that exist in the 'micro world', become the center of attention and are studied as entities that carry their own history and are acted upon by their owners. This perspective produces a new view of the process, according to which the solution is made up of structural components that are "owned" by actors who have contributed in various degrees to the produced solution. This view of the world, which is a reversed view of the one we usually build of the problem solving process can be useful, as it reveals the contribution of the various actors in parts of the solution, identifies areas of intense collaboration in relation to the final solution and can relate easily to other analysis frameworks like interaction analysis.

According to this view an operational framework of analysis and evaluation of collaborative design problem solving has been defined called 'Object-oriented Collaboration Analysis Framework' (OCAF) (Avouris, Dimitracopoulou, Komis, & Fidas, 2002). Its corresponding analytic model identifies patterns of interaction and relates them to objects of the shared design solution. The model provides a new way of representing collaborative design problem solving activity and supports qualitative and quantitative representations that can be used as analysis and evaluation tools. It should be noticed that the term "object-oriented" in OCAF is not related to the software engineering term, but it refers to the parts of the shared design solution.

The framework has been used for the analysis of various kinds of collaborative design problem solving environments, based on jointly developed diagrammatic 'design solutions', made of well distinguished objects, such as concept maps, entity-relationship diagrams, data flow diagrams, diagrams of specific modelling formalisms or design formalisms, architectural diagrams, etc. The design solutions need to be represented by three basic constructs: entities, relationships and attributes of the entities. The available tools for computer-supported collaborative design problem solving are numerous, given that during the last years the research community has focused on the design and development of such tools, putting special emphasis on the affordance of representations involved on supporting reasoning.

In this paper, after a short review of analysis approaches on technology-based collaborative problem solving, a notation of the OCAF model is proposed. Subsequently, two examples of use of the framework in synchronous collaborative design problem-solving situations are presented. It is shown through these examples that this approach can be applied both in synchronous distance-collaboration environments (case A) and in co-located group collaboration (case B). A discussion on the applicability of the approach in other cases of collaborative problem solving is included in the last part of the paper.

2. On analysis approaches of collaborative problem solving

A substantial number of approaches have been developed for the analysis of collaborative activities in different mediums and environments. Some of them are focused on problem solving strategies or on plan recognition (Hoppe & Ploetzner, 1999), others on the evaluation of partners' involvement (Simmof, 1999), or on the process of mutual understanding and the learning effects (Baker et al., 1999). There are approaches of analysis implemented after the interaction and others that are applicable during the evolution of the collaborative process, thus providing assistance tools that are able to evaluate personal contribution and visualise collaboration patterns (Simmof, 1999).

Collaboration analysis is most often based on analysis of naturally occurring *dialogue*. Researchers are concentrated either on analysis of natural dialogue (O'Malley et al., 2000), or on dialogue through written messages, (Dillenbourg & Traum, 1999). The analysis of collaborative *task oriented discourse* is based on different specific dialogue analysis approaches putting emphasis for instance on *initiative changes*, or on shifts of the *discussion focus* (Burton, Brna, & Pilkington, 2000).

In the following, the field of technology-based collaborative problem solving related to *diagrammatic solutions* is examined through four representative research and analysis approaches.

One characteristic research effort in this area concerns the networked collaborative concept mapping system produced by CRESST (Chung, O'Neil, & Herl, 1999; Herl, O'Neil, Chung, & Schacler, 1999). This is a closed concept mapping system (knowledge mapping according to authors) where the analysis or the model of the problem is based on produced diagrams involving *nodes* representing concepts and *arcs* representing the relationships. The research was intended to measure collaborative team process and team learning outcomes. In order to measure student's domain knowledge and collaboration skills, teams of students were requested to construct semantic relationships among important concepts in the domain of environmental science. Groups collaborated synchronously, sending messages to each other using CRESST collaboration software. The teamwork process was measured by examining predefined message usage, classified according to a specific taxonomy, while the solutions provided were measured by scoring each team's concept map using four expert maps as criterion. The evaluation process involved both pre-test and post-test phases. The relation between team process and team solutions was studied by a correlation analysis.

The work of Muhlenbrock and Hoppe (1999) is interesting in terms of group interaction analysis. In this work a system for automated task-oriented analysis of collaborative problem solving has been developed, applicable on problems that can be solved by spatial arrangement of cards (e.g. puzzles). The analysis is focused on plan recognition and problem solving activities (such as aggregation, conflict creation, revision). During the online processing of the action protocol, high level descriptors of users' actions are derived from which advise to the users is produced.

The analysis is action-based, while messages analysis or natural dialogues analysis is not included in the study.

A third significant research on collaborative problem solving using diagrammatic and verbal communication, is related to C-CHENE system (Baker & Lund, 1997; Baker et al., 1999). The C-CHENE system was designed to support dyads of students collaborating in the construction of diagrams of energy chains, i.e. qualitative models for energy storage, transfer and transformation. One of the related studies involved investigations of the effect of different kinds of message-based communication interfaces (allowing free text, or based on a restricted set of communicative acts) on collaborative interaction patterns that favor learning. The evaluation was based on qualitative aspects of the interaction that learners produced while using the system. In the frame of this analysis, a comparison between the object manipulation actions and the communicative acts of the students was performed. Furthermore, a classification scheme was developed, that comprised nine subcategories of communicative acts and a unique category of actions related to the construction of the diagrams.

Finally, BELVEDERE v.2 is a networked software system allowing students to collaborate during scientific inquiries (Suthers, 1999a,b). Its core functionality is a shared workspace for constructing 'inquiry diagrams' which relate data and hypotheses by evidential relations, according to a specific icon-based formalism. Previous research on this system seems to be based more on dialogue analysis of students when interacting with the system (see for instance, Suthers, 1999a). A recent paper (Suthers & Hundhausen, 2001) reports data analysis based on common transcripts of dialogues and actions helping them to compare verbal against representational transcripts segments in three different tools for representing evidential models.

According to the described approaches of collaborative problem solving analysis, it appears that often the dialogues between the participant human actors constitute the main object of analysis, while little attention is put in the produced solution itself. Even when the content of the task/problem solving is taken into consideration, this is viewed in terms of the quality of the produced solution rather than the process of producing this solution. Moreover, it seems that very few of the related research efforts (one is reported above) have based their analysis on the collaborative human agents actions. Finally, even if the general framework of analysis, for instance this related to C-CHENE (reported on Baker et al., 1999) is oriented to a unified approach of actions, tools used and dialogues, it has not lead to a well coordinated analysis of both actions and dialogues, as well as to the components of the reported solutions. This focus is due perhaps to a dominant psychological interest in answering primarily general questions relating to understanding collaborative learning. We believe that the jointly developed solution, if analyzed under an appropriate framework, can reveal complementary aspects of the development of collaboration and participants' roles, while it can be a useful object for evaluation of the educational process. The OCAF framework described in the following section, introduces this complementary analysis perspective.

3. Introduction to *OCAF*

The proposed framework is based on two basic considerations, one related to the '*object* oriented view' of collaborative agents' roles and contributions and the other to the 'unified analysis of *dialogues and actions* on objects'.

(a) The diagrammatic solution of the design problem is a representation of the shared effort of the involved partners as well as of their shared memory. In OCAF we shift the centre of attention on these objects of the solution. That implies that these objects, constitutive of the solution, are studied as entities that carry their own history and are acted upon by their owners (the actors involved in their conception, creation, modification, inter-relation in the specific diagrammatic solution provided by them). This perspective produces a new view of the process, according to which the solution is made up from structural components that are "owned" by actors who have contributed in various degrees to the produced solution. This "object oriented view" focuses on the ownership of the constitutive objects of the solution, covering also parts of the solution that have not been completed or have been rejected in the process.

(b) Previous research has shown (Baker et al., 1999) that mutual understanding among the collaborative agents takes place via a combination of *perception of graphical action* and *communication*. Furthermore, depending on the provided tools facilitating dialogue, the collaboration mode can vary from a more action-dominant mode to a more discussion-based mode. For these reasons, it is argued that there is a need to apply a unified analysis and interpretation of both dialogue and actions related to the solution objects, in order to analyze and evaluate collaborative activities in diagrammatic problem solution.

From the resulting framework of analysis, a model M of the solution is defined, conceived in this context, as a formal model, that can be used to analyze or reconstruct certain aspects of both actions and dialogues occurring in the problem-solving group. This model of ownership of the solution is based on the notion of ownership of the components of the diagrammatic solution. Such a diagram in many cases is made of objects (entities) that are shown in the diagram in abstract or pictorial form. These can be related through relationships often shown or implied in the solution. The entities have attributes or properties that are associated to them. The entity/relationship/attribute constructs could be the basic objects that make a diagrammatic solution according to the proposed framework. Most of the problems and solutions studied in the frame of our work were made of these basic constructs. However in more complex problems than the examples discussed here, higher order structures can often be defined. These can be abstract objects containing parts of the diagram and can be defined in a recursive way. The actors can reason about these parts of the solution, which they can test, dispute or modify considering them as higher order entities. These composite objects can also be defined in terms of the primitive objects if they appear in the discourse and the OCAF model can accommodate them in the same way as it handles the primitive objects.

The proposed model according to OCAF has been formalized in textual and diagrammatic form as follows:

If a given solution S of a problem X, $S(X) = \{E_i, \quad R_j, \quad A_m\}$, where E represent the node entities of the solution, ($i = 1, \ldots, k$) R the relationships connecting them ($j = 1, \ldots, l$) and A the attributes of the entities ($m = 1, \ldots, n$) that participate in the solution.

The model of the solution can be:

$$M(S) = \{Ei \quad {}^*\tau_i/P_i f_j, P_k f_l, \ldots R_j \quad {}^*\tau_i/P_i f_j, P_k f_l, \ldots, A_m \; {}^*\tau_i/P_i f_j, P_k f_l, \ldots; \\ -E_i \quad {}^*\tau_i/P_i f_j, P_k f_l, \ldots - R_j \quad {}^*\tau_i P_i f_j, P_k f_l, \ldots, A_m \; {}^*\tau_i/P_i f_j, P_k f_l, \ldots\}$$

where: E, R, A, are the entities, relations and attributes that are part of the final solution, while with $-E$, $-R$, $-A$ the items discussed during the problem solving process, but not appearing in the final solution, are shown. τ_i is an index of the item, as implied by its initial action of insertion or by its discussion in the timeline of the problem solving process.

To each item a sequence of $P_i f_j$ is associated. Each $P_i f_j$ represents the human agent P_i (e.g. a student, teacher or facilitator) participating in a direct or indirect way in the problem solving process and his/her functional role f_j related to the particular part of the solution.

The different functional roles f used in OCAF are described in Table 1. It should be noticed that two functional roles concern the initial proposition to insert the item [by action (I) or by dialogue (P)], while the others express the discussion on each item. Also testing of the proposed solution is done through argumentation (A) in the case of static-diagrammatic solutions, while testing can involve use of alternative representations and provided testing tools in case of development of dynamic models of the solution (T).

So for example: [E (Storehouse)] = $A_P B_M A_I$ indicates that the entity *Storehouse* has been produced from interaction of Agents A and B. Agent A made the initial proposal (A_P), which was modified subsequently by Agent B (B_M), finally Agent A inserted the object in the shared Activity space (A_I), accepting the final solution.

It has to be noticed that the actors' functions in interaction have been defined as 'functional roles' of 'communicative acts'. Initially, the 'functional role', was a term used in dialogue analysis by linguistics (Moeschler, 1986, 1992; Roulet, 1986), transferred in educational research (Sabah et al., 2000) in the context of verbal dialogues. A 'communicative act' (Baker & Lund, 1996; Bunt, 1989; Burton et al., 2000) was a term referred on both oral and written communication. In our context, the term of 'communicative act' refers not only on messages (written dialogues during collaboration by distance), and oral utterances (during face to face collaboration), but also on actions of collaborative agents, given that during a synchronous collaborative activity these actions have a strong communicative status. Consequently, in our context of computer-based collaborative problem solving, a functional role reports the purpose of a 'communicative act', from the point of view of its 'actor' or 'interlocutor', thus constituting an interpretation of the actors/interlocutors intention in communication.

Table 1
Unified "functional roles" definitions

ID	Functional role	Derived from:	Example
I =	Insertion of the item in the shared space	Action analysis	*Action:* 'Insertion' of Entity "Velo"
P =	Proposal of an item or proposal of a state of an item or of an action (P[= action])	Dialogue analysis	*Message:* "I believe that one entity is the firm 'ABC'" or "let us put the value of entity flow to state locked"
C =	Contestation of the proposal	Dialogue analysis	*Message:* I think that this should be linked to the entity B by the "analogue to" relation
R =	Rejection/refutation of the proposal	Action and/or dialogue analysis	*Message:* "What their attributes will be? I don't agree". Or *Action:* 'Delete' Entity "Velo"
X =	Acknowledgement/acceptance of the proposal	Action and/or dialogue analysis	*Message:* "That's right" or *Action:* Insertion of a proposed enitity
M =	Modification of the initial proposal	Action and dialogue analyses	*Message:* I suggest we put the state to "unlock" *Action:* "Modify"
A =	Argumentation on proposal	Dialogue analysis	*Message:* "I believe that I am right because this is . . ."
T =	Test/Verify using tools or other means of an object or a construct (model), T[= tool-name]	Actions and dialogue analyses	*Message:* Let us run this model to observe this part of the model behavior *Action:* Activate 'Graph Tool', or ' Barchart Tool'

An alternative, *diagrammatic representation* of the model involves association of the solution items to their history as shown in the following Fig. 1. In the same figure a legend of the symbols used for the diagrammatic representation of the model is also included. The advantage of the textual representation is that it can be produced and processed by an adequate tool, while the diagrammatic representation is easier for humans to study. The two representations of the model are equivalent.

4. Case studies of OCAF application

In this section application of the OCAF framework is presented in two different collaborative problem solving settings:

- Students working in a synchronous mode at a distance in order to build a data model in the frame of a University-level undergraduate Databases course. The environment used in this case was the "Representation v.2" System (Fidas, Avouris, & Komis, 2001). The collaboration was effected

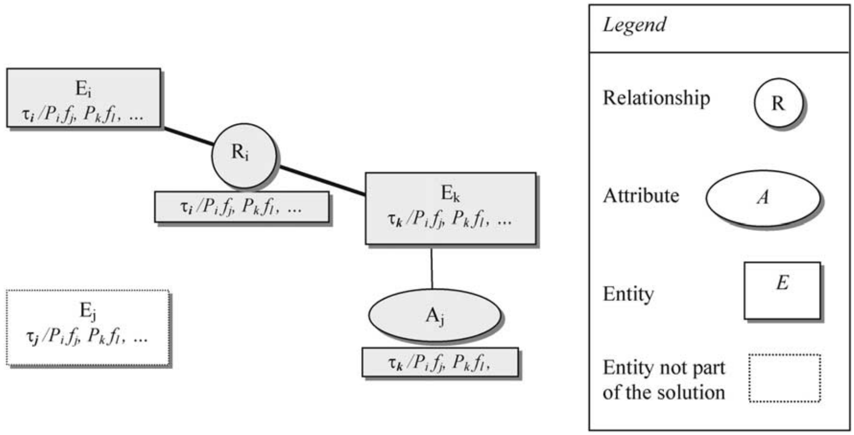

Fig. 1. Diagrammatic representation of solution's OCAF model and legend of symbols used.

though exchange of chat messages and actions in a shared workspace in which the developed common solution appeared.

- Face to face collaborative problem solving, involving two secondary school students, in the presence of a tutor experimenting with modeling the relations between simple entities. The environment used was the MODELS-CREATOR (Dimitracopoulou, Komis, Apostolopoulos, & Politis, 1999). The analysis is based on recorded oral dialogues as well as on the students' actions on entities, properties and relations of a developed model.

In the following sections typical extracts of analysis are included. Subsequently a discussion on the applicability of the technique in other cases of collaborative problem solving is provided.

4.1. Case A: collaborative distance problem solving

The first case study involves use of Representation V.2., a system for synchronous collaborative problem solving, expressed through semantic diagrams. The system supports the simultaneous development of these diagrams by partners situated at a distance, through the use of a shared 'Activity Space', an extract of which is shown in Fig. 2.

The case study, discussed also in Komis, Avouris, and Fidas (2002), is taken place in the context of a University undergraduate course. The problem solving task involved the collaborative building of a data model of the activities of an imaginary goods transport company (ABC) that supplies the stores of a supermarket chain (VELO), transporting goods from a number of storehouses owned by the super-market company to the supermarket stores. The purpose of this model is to be used in the design of a database to support the companies involved in scheduling their trucks and delivery of supplies. The students had to express the model as an entity-

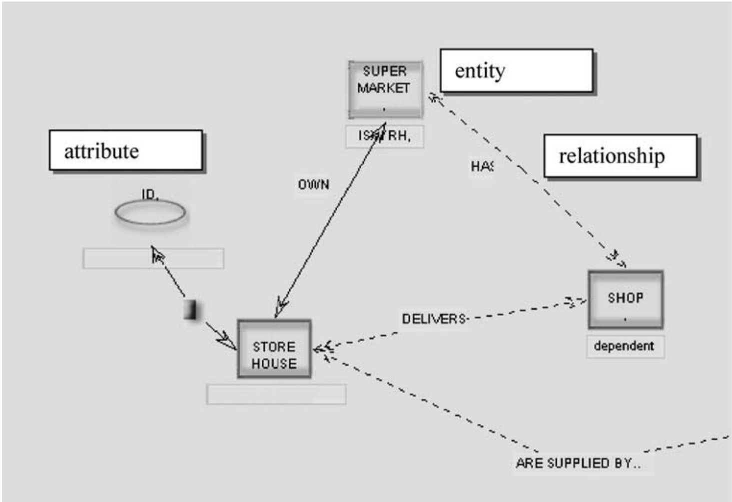

Fig. 2. An extract of the working area of R2 during the discussed case study.

relationship (ER) diagram, a representation often used in data modeling (Chen, 1976).

The main objective of the experimentation was to study the degree of collaboration and the development of problem solving strategies. Main sources of data for our analysis have been the log files, which contain details of inter-group communication acts (chat messages) and shared activity space actions, as well as the produced ER diagrams of the students. An extract of this log file, as well as its interpretation in terms of OCAF functional roles is shown in Table 2.

An example of analysis of collaborative solution is presented here. The problem solving team studied in this section is made of students E and F. The produced solution by this group is modeled, according to the OCAF framework, as following:

$M_{EF} =$	{Entities =	E (ABC) =	$1/E_P, F_A, E_I$
		E(VELO) =	$2/E_P, F_A, E_I$
		E(TRUCK) =	$3/F_P, F_I$
		E(STOREHOUSE) =	$4/F_P\ E_C, F_A, F_I$
		E(STORE) =	$5/F_P\ E_C, F_A, F_I$
		E(DELIVERY) =	$11/F_P, E_X, F_I$
	Relations =	R(VELO-owns-SH) =	$9/F_{PI}$
		R(VELO-owns-ST) =	$10/F_{PI}$
		R(TRUCK-transports-DELIVERY) =	$17/E_P, F_I, E_C$
		R(SH-is-suppplied-by-TR) =	$18/F_{IM}$
		R(ABC-owns-TR) =	$26/F_{PI}$
		R(ST-owns-SH) =	$24/E_P\ F_P\ F_I\ E_C, E_M$
	Attributes =	A(DEL.id) =	$13/F_{IM}$
		A(DEL.volume) =	$14/F_{IM}$

A(DEL.Weight) = $15/F_I$
A(DEL.Destination) = $16/F_I$
A(TR.Max_Weight) = $19/F_I$
A(TR.id) = $21/E_P, F_I$
A(TR.Journey_id) = $23/F_I$
A(TR.volume) = $20F_{IM}$
A(SH.id) = $25/F_I$

Items not in the final solution

−R(SH−DEL) = $12/E_P, F_R$
−A(VELO.Storehouse) = $6/E_P, F_C$
−A(VELO.Store) = $7/E_P, F_C$
−A(ABC.Truck) = $8/F_P, E_X$
−A(TR.max_journeys_per_week) = $22/E_P, F_R$ }

Table 2
Extract of interaction between partners E and F, in case study A (τ_i = index of solution items)

Partner E (actions and messages)	Partner F (actions and messages)	Functional roles	τ_i
E: ... about the entities, strong entities are ABC and VELO		ABC: E_P	1
		VELO: E_P	2
	F: Yes and also TRUCKS, STOREHOUSES and STORES	ABC: F_A	
		VELO: F_A	
		TRUCK: F_P	3
		STOREHOUSE: F_P	4
		STORES: F_P	5
E: Attributes of (supermarket) VELO are the STOREHOUSES and the STORES		VELO.STOREHOUSE: E_P	6
		VELO. STORES: E_P	7
	F: and attributes of ABC the TRUCKS	ABC.TRUCK: F_P	8
Added rectangle object			
	F: No they are not attributes they are weak entities	VELO.STOREHOUSE: F_C	
		VELO. STORES: F_C	
		STOREHOUSE: F_A	
		STORES: F_A	
E: ...and for ABC the TRUCKS (are attributes) and we need to show the JOURNEYS somehow		ABC.TRUCK: E_X	
The rectangle object is named VELO		VELO: E_I	
	F: I cannot see what you are doing	(Control statement)	
Added object-named object ABC		ABC: E_I	
	Could you pass me the action key please?	(Control statement)	

The last five items of the M_{EF} model concern objects discussed during problem solving process but not reported in the final solution due to conflicts between collaborating agents or not completed negotiation. The same model is shown in diagrammatic form in Fig. 3.

4.1.1. Analysis supported by the model

From this descriptive model, a qualitative analysis may concern the appropriateness and completeness of the proposed solution. So for instance the relation *Storehouse owns Trucks* is not correct, since such ownership is not included in the problem description. The correct relationship could have been *Trucks are loaded at Storehouses*. It is also observed that this relationship has not been subject of strong collaboration. It is also interesting to study the parts of the solution that lead to conflicts and did not take part in the final solution. For instance Actor E proposed *Store* as an attribute of entity VELO that was abandoned in favor of inserting *Store* as a separate entity, a solution that is more appropriate for the specific problem.

The model, as discussed in the following, can support a quantitative analysis orientated to the *solution items*: Number of items in the model = 20, Number of items discussed and not included in the final model = 5, Number of items of unresolved conflicts = 4.

Quantitative analysis oriented to *interaction patterns* identifies (10) different interaction patterns in the model. The items produced per interaction pattern are:

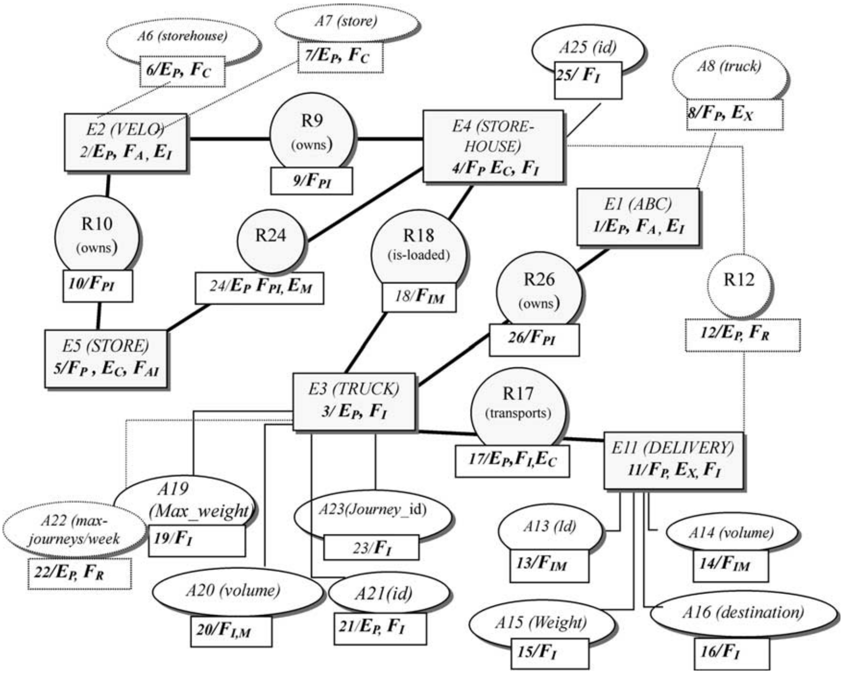

Fig. 3. The solution expressed as OCAF diagrammatic model.

$F_{I=}5$ (item inserted by F implicitly accepted by E)
$F_{IM=}4$ (item inserted by F, subsequently modified by same actor)
$F_{PI=}3$ (item proposed by F and subsequently inserted by the same actor)
E_P $F_I=2$ (proposed by E and inserted by F)
F_P E_C F_A $F_{I=}2$ (item proposed by F, contested by E, acknowledged argument by F and finally inserted by F)
E_P $F_{R=}2$, E_P $F_{C=}2$ (item proposed by E and proposal rejected or contested by F with no further discussion)

Patterns that occurred once are: F_P E_X F_I, E_P F_I E_C, E_P F_A E_I, E_P F_X, F_P E_C F_A

If the analysis is *oriented to contributors* (in this example students E and F), one can determine that in this collaborating team, 25 items have been discussed of which 12 have one owner and other 13 two owners. The *distribution of items* proposals among the agents involved (strong indication of ownership and involvement) is: E = 4 (20%), F = 16 (80%), while four more items proposed by E and one proposed by F did not take part in the final solution.

The distribution of functional roles among the partners is shown in Table 3.

The possession of the *action-enabling key* (permitting actions on the shared workspace to its owner) was 40% of the time for E and 60% for F. According to Table 3, the holder of the key takes stronger action roles (e.g. I, M), while the observer (F) takes stronger verbal roles (e.g. P, C).

If the analysis is orientated to the *content*, i.e. the items of the solution in relation to ownership, it is observed that the most important items of the developed solution (i.e. entities and relationships) are eight of dual ownership (67%) and four of single ownership. In other words there has been *stronger interaction* in the process of creation of the backbone parts of the solution than the secondary parts (i.e. attributes).

4.2. Case B: face to face collaborative problem solving

This case study involves a group of two 15-year-old pupils (A and B) working as a group, in the presence of a facilitator F (a teacher-researcher). The experimentation takes place in a laboratory. The students are asked to study a simple situation where a barrel can be filled by the water of a tap and build a model of the relations involved using MODELSCREATOR, a learning environment allowing creation and testing of models using pre-defined objects (Dimitracopoulou et al., 1999; Komis, Dimitracopoulou, Politis, & Avouris, 2001). The environment is a single-user tool,

Table 3
Functional roles of partners of case study A

Partner	Total	I	P	C	R	X	M	A	T
E	16	1	9	4	0	2	0	0	0
F	38	18	7	2	2	1	4	4	0

so one of the pupils is the operator of the tool, while the second pupil and the facilitator are observers. In order to build a solution, the pupils have to determine the relevant entities, their properties and the relations between them.

The pupils have chosen to use semi-quantitative relations (e.g. is-proportional-to, is inversely-proportional-to etc.) expressing the variation of inter-related properties and direction of this variation between them. Thus, the pupils had to think about the entities involved in the situation, define their properties (the tap's rate of flow, the time and the volume of the water filling the barrel) and determine the relations between them (see Fig. 4). In order to test a model, the pupils could run a dynamic model and observe the behavior of entities (tool SIMULATION or STEP-SIMULATION), change the value of an attribute manually and observe the effect on the model (tool M-SIMULATION), lock the value of an attribute (tool LOCK). They can also activate representational tools: graphs (tool GRAPH), bar-charts (tool BARCHART), etc.

The sources of research data were the keystrokes log files, and the videotape transcription of the dialogue between the students and the facilitator, synchronized with video transcript of the screen activity. Unified transcripts were produced for the group, containing both actions (provided by log files) and dialogues (provided by video).

A typical extract of analysis of the collaborative solution is presented here. The problem solving team studied in this section is A–B–F comprising a group of two students (A, B) solving a problem and the tutor called F (Facilitator).

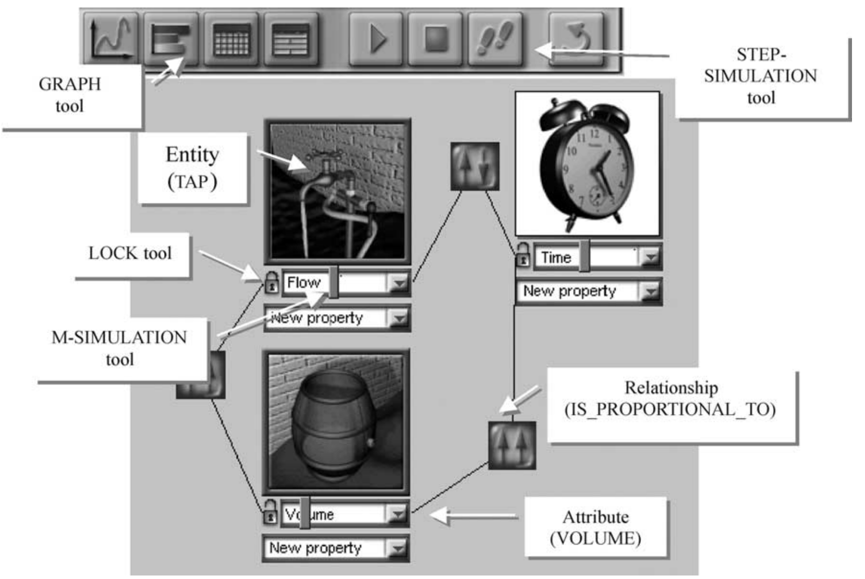

Fig. 4. An extract of the working area of MODELSCREATOR environment.

For group A–B–F the produced OCAF model contained the following items:

$M = \{$

Entities E (TAP) $= 2/A_I A_C F_C B_X\ A_X$

E (BARREL) $= 1/A_I$

E (CLOCK) $= 6/B_P A_X A_I$

Attributes A(TAP.flow) $= 4/A_P A_I F_{P=T} B_{P=T} A_{T=LOCK} A_P A_{T=LOCK} A_{T=M\text{- }SIMULATION}$

A(BARREL.watervolume) $= 5/B_P\ A_I\ A_A B_A A_A$

A(CLOCK.time) $= 7/A_P A_1 A_A B_{P=T} A_{T=LOCK}\ A_{T=M\text{-}SIMULATION}$

Relationships R(FLOW$_{(tap)}$–$_{\text{Proportional-to}}$–WATERVOLUME$_{(barrel)}$ $= 11/A_P A_P A_I$ $F_{P=T}\ A_{T=BARCHART}\ A_A\ B_A$

R(FLOW$_{(tap)}$–$_{\text{Inverse-Proportional-to}}$–TIME$_{(clock)}$ $= 14/A_P A_I$

R(WATERVOLUME$_{(barrel)}$–$_{\text{Proportional-to}}$–TIME$_{(clock)}$) $= 8/A_P\ A_I$ $F_C\ A_A\ A_{P=T}\ A_{T=M\text{-}SIMULATION}\ A_{T=SIMULATION}$ $F_{P=T} A_{T=M\text{-}SIMULATION}\ A_{T=SIMULATION}\ A_R\ A_I\ A_R\ F_A\ A_I$

Items proposed and not inserted or finally rejected are:

–E (cistern) $= 3/A_P F_C\ B_C\ A_P\ F_C\ B_P\ A_P\ F_C\ A_A\ A_R$

–R (FLOW$_{(tap)}$ –$_{\text{Inverse-Proportional-to}}$–WATERVOLUME$_{(barrel)}$) $= 9/B_P\ A_I\ A_{T=M\text{-}SIMULATION}\ A_R\ F_A\ A_I\ F_{P=T}\ A_{T=M\text{-}SIMULATION}$ $A_{T=SIMULATION}\ F_{PT}\ A_{T=STEP\text{-}SIMULATION}\ B_A\ A_A F_C\ A_A\ F_{P=T}$ $A_{T=SIMULATION}\ A_R\ F_C\ B_A\ F_{P=T}\ F_{T=M\text{-}SIMULATION}$ $F_{T=M\text{-}SIMULATION}\ B_R\ F_M$

–R (FLOW$_{(tap)}$–$_{\text{Proportional-constant-to}}$–TIME$_{(clock)}$) $= 10/A_I\ F_A\ A_A\ A_R$

–R (FLOW$_{(tap)}$–$_{\text{Proportional-square-to}}$–WATERVOLUME$_{(barrel)}$) $= 12/A_P\ A_I\ A_{P=T}\ A_{T=BARCHART}\ A_C\ B_P\ A_R\ A_M$

–R (FLOW$_{(tap)}$–$_{\text{Proportional-constant-to}}$–WATERVOLUME$_{(barrel)}$) $= 13/B_P A_C\}$

The last five items of the model concern items discussed during problem solving process but not reported in the final solution provided, due to unresolved conflicts, between the agents.

This model is also represented in diagrammatic form in Fig. 5.

4.2.1. Analysis supported by the model

From this descriptive model, a qualitative analysis, concerning the items themselves, determines the appropriateness and completeness of the proposed solution. Such a qualitative analysis could also provide information derived from the order/index of items discussion (variable τ_i). For instance, the entity CLOCK ($\tau_i = 6$) is inserted with some delay, due perhaps to the abstract nature of the concept of time. Additionally, it should be observed that the presence of F (facilitator) appears decisive in early stages (e.g. items 3, 8, 9), while the rejection of incorrect parts of the solution at a later stage (e.g. items 12 and 13) is done by the pupils themselves with no intervention of the facilitator.

A quantitative analysis orientated to the *solution items* can be supported, as follows: Number of items in the model = 9; Number of items discussed and not included in the final model = 5; Number of items of unresolved conflicts = 1.

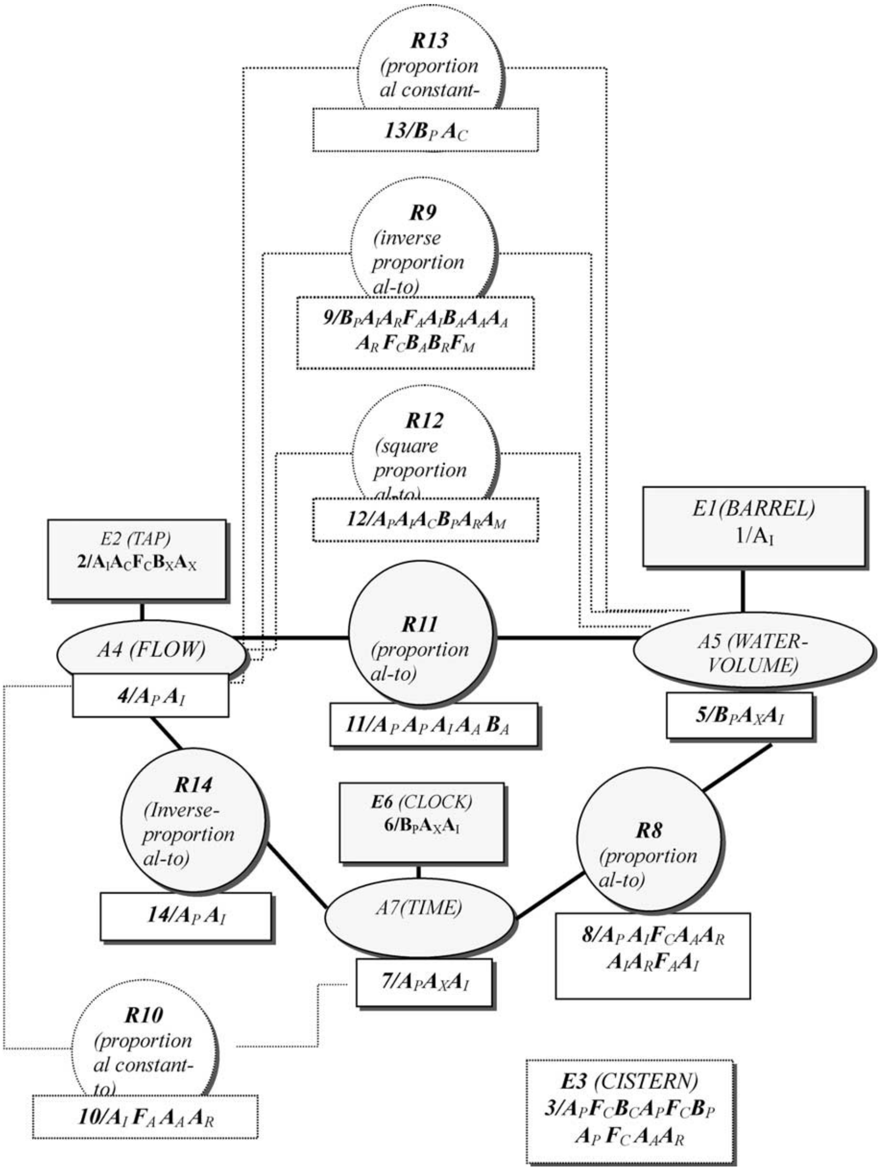

Fig. 5. The solution expressed as OCAF diagrammatic model.

Quantitative analysis oriented to *interaction patterns* identifies the rich interaction that took place due to the presence of the facilitator, the co-location of actors and the presence of tools that were used to validate alternative solutions. In relation to the problem-solving strategies and use of tools, it is observed that the pupils have tested parts of the solution (e.g. the relations) by using mostly manual simulation (M-SIMULATION) and did not validate the overall model, due perhaps to the simple structure of the developed model. Alternative representations like bar-charts have also been used in a limited degree.

If the analysis is *oriented to contributors* (A, B and F), one can determine that in this collaborating team, 14 items have been discussed, of which two (14%) had one owner, seven had two owners (50%) and five had three owners (36%). From the objects of multiple ownership most of them have been assigned long interaction patterns, indication of strong interaction about the concepts involved.

If the analysis is *oriented to the content*, the items of the solution provided in relation to the ownership, it is observed that the most collaborative activity concerns the relationships (R). The objects themselves are inserted without many objections and therefore they do not become objects of discussion. Also the *attributes* did not involve strong interaction, however, this is understandable since the entities involved had single properties, so there was no selection involved in relation to the entities *attributes*. One observation on the density of collaboration is that there is a lot of interaction on objects not inserted in the model (e.g. relationship inverse-proportional between *water-volume* and *tap-flow* and on entity *Cistern*, see Fig. 5). The intervention of the Facilitator plays an important role in resolving the conflicts in these occasions. Surprisingly the relationship between elapsed-time (the time required to fill certain volume of water) and tap-flow, which is conceptually the most difficult one (inverse-proportional-to) did not create major conflicts as it was introduced by ($14/A_P\ A_1$). However it is assumed that the concept has been constructed through the collaborative activity that took place in relation to earlier parts of the solution and the alternative representations of the model used, since this relationship has been one of the last ones introduced.

Finally, the *distribution of items* proposals among the agents involved (strong indication of ownership and involvement) is as following: A = 10 (71%), B = 4 (29%), F = 0, ratio = 2.5. It should be observed that actor A was mainly the operator ('Insertions' from A = 15 and 'Insertions' of B = 0, see Table 4), so this non-uniform distribution of ownership reflects these roles.

5. Discussion

The collaborative problem solving analysis framework OCAF presented here is based on two considerations: (a) the notion of 'solution ownership' expressed as contribution of the actors to the parts of the produced solution, (b) the unified

Table 4
Functional roles of partners of case study B

Partner	Total	I	P	C	R	X	M	A	T
A	65	15	12	3	7	2	1	9	16
B	15	0	8	1	1	1	0	4	0
F	18	0	7	5	0	0	1	3	2

analysis of dialogues and actions. The framework has been applied in two cases of synchronous collaboration between students working on a shared workspace. Since the reported case studies a number of additional studies have been performed by our group, confirming the validity and usability of the framework. In this section the main conclusions of the reported study are discussed.

Collaboration is a phenomenon for which we lack adequate analytic models. It is not claimed that the complex phenomena of social interaction and particularly of collaborative learning can be comprehensively reconstructed by analytic models. These models are bound to be partial, capturing only specific facets of actions or interactions in groups. The value of an analytic model like OCAF, is related to its capacity to bring up interesting points of view and thus provide information to researchers aiming at answering questions relating to some of the following issues:

- Degree of participation of group members, based on indicators such as distribution of solution items per members.
- Contribution of group members to the developed solution.
- Determination of roles of group members, e.g. based on degree of involvement and role of specific members such a teacher or a facilitator.
- Density of interaction.
- Identification of interaction patterns per item of solution.
- Order of appearance of specific items in the solution.
- Identification of tools and strategies used for solution validation.

Some of the above points are related to quantitative aspects of interaction, and appear often in studies of collaborative distance learning environments, while others relate to a more cognitive and meta-cognitive view, as for instance is the case of solution validation strategies. These questions have been effectively tackled using OCAF, as demonstrated in the case studies presented.

A second point relates to the diagrammatic form of the OCAF model. This contributes in a supplementary way to the analysis, providing a perceptual view on these parameters. This view can directly be related to the produced solution, associating the history of interaction to the items involved. Also items discussed but not included in the solution appear in this view. One can consider this view as an attempt to relate the time dimension (predominant in interaction analysis) to the space dimension (predominant in diagrammatic solution representation). Various transformations of this view can make it suitable for different users. For instance, by adequate color-coding of the participants and their roles, the association of ownership to solution items could become vivid, supporting reflection of problem solvers or teachers in a metacognitive level.

The OCAF model provides an object-oriented perspective, supporting an ownership and contribution per item perspective and an interaction/collaboration effort perspective. Thus, it is not limited to a *social vs cognitive* dimension of analysis or a *task/communicative* one (Dillenbourg et al., 1996), but can lead to a combination to different dimensions of analysis: a social vs cognitive-task oriented perspective, as well as a cognitive vs metacognitive one.

One issue worth further investigation is the generality of the OCAF approach. The framework was applied in two cases, both of them involving diagrammatic problem solutions where the constitutive items of the solution where entities, relations and attributes or properties. It is believed that by using the framework, similar models can be produced containing various kinds of solution items, the only restriction being that the problem solution is made of independent items. So many diagrammatic or object-based solutions, like diagrams, puzzles, etc., can be analyzed. In contrary, this framework cannot easily be applied in text-based or algebraic solutions. Additionally, the framework can be applicable in different collaborative settings, synchronous, distance collaboration or face-to-face situations, as demonstrated in our case studies. These affect the communication media and tools used (natural dialogue or text messages), and consequently the corresponding part of analysis unit (the message, the utterance, etc.). The question of applicability of the proposed framework in cases of asynchronous collaboration is subject of further research.

Also the generality of the actors' *functional roles* are worth further consideration. One can expect that some functional roles might need to be modified, as they are attributed to both actions and dialogues of actors in specific cases, however these modifications do not affect the generality of the framework.

One of the prime advantages of the proposed framework is that the OCAF model can be generated and processed by adequate automatic tools, attached to a collaboration support environment, like Represenation v2 and ModellingSpace. In particular, the *action part* analysis can be directly automated, while the *dialogue part* needs dialogues analysis approaches. These OCAF-compatible analysis tools could be used by teachers managing on-line distance collaborative problem solving. Also tools for collaboration visualization can be produced that can be even used by the students themselves as *metacognitive tools* in order to help them self-regulate their collaborative or problem solving process.

In conclusion, it should be stressed that the focus of the presented research is on the analysis of problem solving as an educational activity, rather than on answering general questions related to collaboration and learning. The OCAF approach is mostly geared towards use of collaborative systems in every day educational practice, where there is an urgent need to analyze and evaluate both learning outcomes and quality of collaboration in an operational way.

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