CM-RELVIEW: A Tool for Causal Reasoning in Multiagent Environments

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Abstract

Analytical techniques are generally inadequate for dealing with causal interrelationships among a set of individual and social concepts. In this paper, we present a software tool called CM-RELVIEW based on relational algebra for dealing with such causal interrelationships. Then we investigate the issue of using this tool in multiagent environments, particularly in the case of: (1) the qualitative distributed decision making and, (2) the organization of agents considered as a wholistic approach. For each of these aspects, we focus on the computational mechanisms developed within CM-RELVIEW to support it.

Index Terms— Decision support, cognitive maps, knowledge base management, tools and supports, causal maps, agent and multiagent systems.

1 Introduction

Cognitive maps follow *personal construct theory*, first put forward by Kelly [9]. This theory provides a basis for representing an individual's multiple perspectives. Kelly suggests that understanding how individuals organize their environments requires that subjects themselves define the relevant dimensions of that environment. He proposed a set of techniques, known collectively as a *repertory grid*, in order to facilitate empirical research guided by the theory. Personal construct theory has spawned many fields and has been used as a first step in generating cognitive maps. Huff [8] has identified five generic "families" of cognitive maps:

1. *Maps that assess attention, association and importance of concepts*: With these maps, the map maker searches for frequent use of related concepts as

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indicators of the strategic emphasis of a particular decision maker or organization, for example, and look for the association of these concepts with others to infer mental connection between important strategic themes. She also might make judgments about the complexity of these relationships or differences in the use of concepts.

2. *Maps that show dimension of categories and cognitive taxonomies*: The map maker investigates here more complex relationships among concepts. She might dichotomize concepts and construct hierarchical relationships among broad concepts and more specific subcategories. Maps of this type have been used to define the competitive environment, and to explore the range and nature of choices perceived by decisions makers in a given setting.
3. *Maps that show influence, causality and system dynamics (causal maps)*: These maps allow the map maker to focus on action, as for example, how the respondent explains the current situation in terms of previous events, and what changes she expects in the future. This kind of cognitive map is currently, has been, and is still, the most popular mapping method.
4. *Maps that show the structure of argument and conclusion*: This type of map attempts to show the logic behind conclusions and decisions to act. The map maker includes here causal beliefs, but looks more broadly at the text, as a whole, to show the cumulative impact of varied evidence and the links between longer chains of reasoning.
5. *Maps that specify frames and perceptual codes*: This approach suggests that cognition is highly conditioned by previous experience, and that experience is stored in memory as a set of structured expectations.

In this paper, we extend the causal map by providing a tool called CM-RELVIEW, which has a precise semantics based on relation algebra [6]. Then we investigate the issue of using this tool in multiagent environments, specially for (1) the qualitative distributed decision making and, (2) the organization of agents considered as a wholistic approach.

1.1 Causal Maps: Motivations Through an Example

Much attention has been recently directed toward the problem of strategic decision making in dynamic and open environments. The issues of this problem tend to become more complicated, unstructured, and not always readily quantifiable. They particularly involve interacting variables that make them difficult to deal with. Analytical techniques have been used to handle well-defined problems, but they are inadequate for this type of problem. A causal map may be employed to cope with complicated problems because it offers to model interrelationships among a variety of concepts. Causal maps (*CMs*) make the following three assumptions about cognition in the context of decision [8]:

1. Causal associations are a major way in which decision problems can be described and understood;

2. Causality is the primary form of post-hoc explanation of decision outcomes; and
3. Choice among alternative decision actions involves causal relations.

Causal maps are usually based on human "communications" collected by interviewing or found in documents such as corporate reports or memos. We are looking there for expressions having the general type:

- "Entity/phenomenon/concept A leads-to/causes/influences/etc. /Entity/phenomenon/concept B" or,
- "B is caused/effected/influenced/etc./ by A".

These are *causal assertions*, which are taken to indicate that the concerned subjects: (1) use concepts (A,B) to refer to some phenomena or concepts in their domains, and (2) think (believe, assume, know, argue, etc.) that there are certain relationships between these concepts.

We generally use causal maps for dealing with such cause-effect relations embedded in deciders' thinking. Theses maps are represented as directed graphs where the basic elements are simple. The concepts an individual (a decision-maker or a group of decision-makers) uses are represented as *points* and the causal links between these concepts are represented as *arrows* between these points. This representation gives a graph of points and arrows, called a *causal map* (*CM*). The strategic alternatives, all of the various causes and effects, goals, and the ultimate utility[1] of the decision-maker can all be considered as concept variables and represented as points in the *CM*. Causal relationships can take on different values based on the most basic values $+$ (positive), $-$ (negative), and 0 (neutral). Logical combinations of these three basic values give the following: "neutral or negative" ($\ominus$), "neutral or positive" ($\oplus$), "non-neutral" ($\pm$), "ambivalent" (a) and, finally, "positive, neutral, or negative" (i.e.,"universal") (?) [1, 5, 13].

The real power of this approach appears when a *CM* is pictured in graph form. It is then relatively easy to see how concepts and causal relationships are related to each other and to see the overall causal relationships of one concept with another, particularly if these concepts are the concepts of several agents.

For instance, the *CM* of Fig. 1, taken from [11], explains how the Japanese made the decision to attack Pearl Harbor. Indeed, this *CM* states that "remaining idle *promotes* the attrition of Japanese strength while *enhancing* the defensive preparedness of the United States, both of which *decrease* Japanese prospects for success in war". Thus, a *CM* is a set of concepts as "Japan remains idle," "Japanese attrition," and so forth, and a set of signed edges representing causal relations like "promote(s)," "decrease(s)," and so forth.

Note that the concepts' domains are not necessarily defined precisely because there are no obvious scales for measuring "US preparedness," "success in war,", and so forth. Nevertheless, it seems easy to catch the intended meaning of the

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[1] Utility means the unspecified best interests of a decision maker.

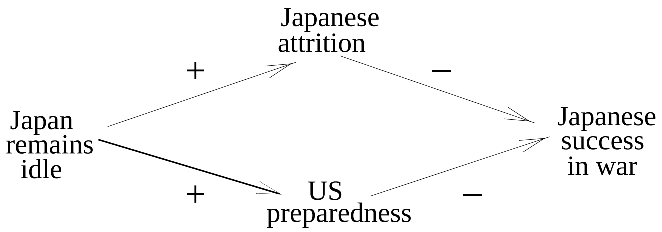

Figure 1: An example of causal map (from [11]).

signed relationships in this model [19]. As any causal map, the *CM* of Fig. 1 can be transformed in a matrix called an adjacency or valency matrix which is a square matrix, with one row and one column for each concept. Thus, if a, b, c and d represents "Japan remains idle," "Japanese attrition," "Japanese success in war," and "US preparedness," respectively, we obtain the following adjacency or valency matrix:

$$\begin{array}{c c} & \begin{array}{cccc} a & b & c & d \end{array} \\ \begin{array}{c} a \\ b \\ c \\ d \end{array} & \begin{pmatrix} 0 & + & 0 & + \\ 0 & 0 & - & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & - & 0 \end{pmatrix} \end{array}$$

Inferences that we can draw from a *CM* are based on a qualitative reasoning similar to "friend's enemy is enemy, enemy's enemy is friend, and so forth." Thus, in the case of Fig. 1, "remaining idle" decreases the prospects for Japanese success in a war along two causal paths. Notice that the relationship between idleness and war prospects is negative because both paths agree. In these conditions, Japan has an interest in starting war as soon as possible if she believes that war is inevitable.

Thus, causal maps and the qualitative reasoning that it sustains serve generally as the modeling language for problem resolution through decision making, particularly in multiagent systems where decision emerges generally from interrelationships among agents' concepts. Such is the case for the previous example that reflects a multiagent system in the sense where "Japan" and "USA" are individual agents.

1.2 Related Work

As previously stated, causal maps appear to be the most widely used cognitive maps in practice. Causal maps have been used for decision analysis in the fields of international relations [1, 5], administrative sciences [15], management sciences [7, 17], and distributed group decision support [21]. In the latter context, Zhang and his colleagues provided the notions of NPN (negative-positive-neutral) logic, NPN relations, neurons, and neural networks. Zhang [20] extended his approach by an NPN fuzzy set theory and an NPN qualitative algebra. In doing so, Zhang and his colleagues focused on quantitative models of *CM*, based on particular techniques for associating intervals with edges of directed graphs. In their model, quantities combine by propagation along paths, but there is no other connection to the original spirit of *CMs*, (i.e., the causal reasoning).

Except for Zhang's work [21, 20], all other approaches to *CMs* were based on simple inference mechanisms about the consequences of a *CM*. Thus, the definition of a precise semantic interpretation of qualitative causality has received very little attention. The only work that we are aware of in this context is Wellman's [19] and Nadkarni's [12] approaches. The first author used an approach based on graphical dependency models, for probabilistic reasoning, and sign algebras, for qualitative reasoning. The second author used Bayesian network approach to making inferences in causal maps. Thus, both used probability theory as is the case usually in Artificial Intelligence. However, their approaches are applicable only in the acyclic case, because circular relations or causal loops, common in causal maps, violate the acyclic graphical structure required in a Bayesian network.

In this paper, we present an implementation of a formal model which has been implemented in a system used as a computational tool supporting the relational manipulations. This tool is called CM-RELVIEW and is built over the RELVIEW software[2], a freeware package developed by Berghammer and Schmidt [2].

2 CM-RELVIEW: An Implementation of a Relation Model of *CMs*

With this tool, all data are represented as binary relations, which the system visualizes in two different ways. For homogeneous relations, CM-RELVIEW offers a representation as *CMs*, including several different algorithms for pretty-printing. As an alternative, an arbitrary relation may be displayed on the screen as a Boolean matrix. With matrix representation, we can visually edit and also discover various structural properties that are not evident from the *CM* representation. CM-RELVIEW system can manage as many graphs and matrices simultaneously as memory allows and the user may manipulate and analyze the relations behind these objects by combining them with the operators of relational algebra. The elementary operations can be accessed through simple mouse-click, but they can also be combined into relational expressions, mapping, and imperative programs. CM-RELVIEW allows also users to store relations and *CMs*.

CM-RELVIEW offers a menu window (as we can show in Figure 2) that can be divided into three parts: the first part, that is the first three button rows, deals with system administration tasks like (a) FILES: opens the file-chooser window;

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[2] This software can be obtained by anonymous ftp from "http://www.informatik.uni-kiel.de/∼ progsys/relview.html".

(b) QUIT: Quits the system; (c) RELATION: Opens the window of the relation editor; (d) GRAPH: Pops the window of *CMs* editor; (e) XRV/PROG: display the directory window showing the state of the workspace and the reasoning on cognitive maps; (f) LABEL: Opens the label directory listing label set which is in our case $\mathcal{C} := \{a, +, -, 0, \oplus, \ominus, \pm, ?\}$.

The buttons in the second part of the menu window cover actions which are mostly needed while working with the system like (g) EVAL: Pops up the evaluation window for entering a relational term (a relational term can be a relation, a function, or a relational program); (h) TESTS: Pops up a window for invoking tests. With the latter window we can perform the following actions (1) TEST-1-R: to execute various kinds of tests on a relation (is it empty, injective, symmetric? etc.); (2) TEST-2-R: to execute tests on two relations (are they equal, included? etc.); (3) SUBJECTIVE VIEWS: to do some tests on *CMs* in the case of the reasoning on subjective views (comparison, prediction and explanation) discussed in details in [6]; (4) WHOLISTIC-CM to execute some strategies of changes on the particular *CMs* representing an organization of agents as discussed in Section 4.

In the third and last part of the menu window, a number of relational operations are directly accessible via push buttons. There is also a directory window that presents the actual state of the workspace to the user.

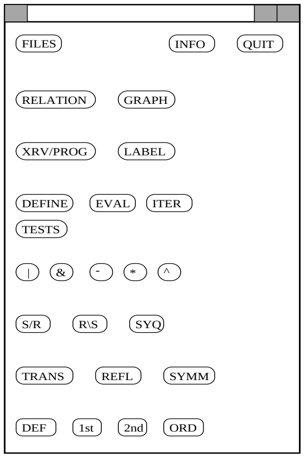
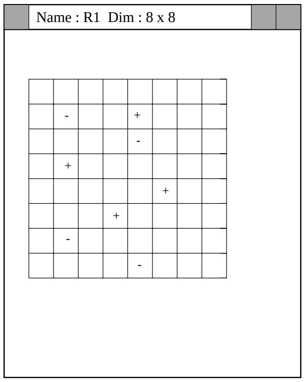


Figure 2: The menu window of CM-RELVIEW.

The relation editor can be opened by clicking onto the button RELATION in the menu window (see Figure 2). Selecting a relation in the first scroll list of the directory window loads this relation into the editor. Evaluation of relational terms performs a load command implicitly, i.e., the result of the evaluation, a relation, is automatically displayed in the relation editor window. There is no explicit “save” command because any modification of the relation shown in the relation editor directly changes the relation stored in the workspace. Typically, the window of the relation editor looks as a grid network in which a single entry of the relation unequivocal defined by a row and a column of a relation is represented by one of the set $\mathcal{C} := \{a, +, -, 0, \oplus, \ominus, \pm, ?\}$. An example of a relation is shown in Figure 3.



Name : R1 Dim : 8 x 8

	-			+			
				-			
	+						
					+		
			+				
	-						
				-			

Figure 3: The relation editor.

If the mouse pointer is located on an item of a relation, the mouse buttons invoke the following different actions: (1) the left mouse button sets the item if it was cleared, or clears it if it was set; (2) the middle mouse button allows to choose one relation (which is used by the left mouse to set) of the set $\mathcal{C} := \{a, +, -, 0, \oplus, \ominus, \pm, ?\}$; finally (3) the right mouse button pops up a menu that appears in Figure 4.

Figure 4: The pop-up menu of the relation editor.

The most interesting menus of the pop-up menu are: NEW: It create a new relation, DELETE: It deletes the relation displayed in the relation editor window from the workspace (the cognitive map associated with the deleted relation is also deleted), RELATION $\longrightarrow$ GRAPH: It creates a *CM* from homogeneous relation with the same name as the relation (such *CM* is displayed in the graph editor). The other menus are easy to understand.

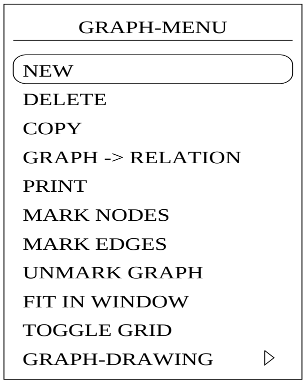


Figure 5: The pop-up menu of the cognitive map editor.

Finally the window of the graph editor (i.e., *CM* editor) can be opened by pressing the button GRAPH in the menu window. Similarly to relations, all actions within this menu are selected with the same right mouse button. By pressing such button, we reach the graph-menu that appears in Figure 5. Within this menu, we can particularly invoke the following actions: DELETE: It deletes all nodes of a *CM*; NEW: It opens a dialog window which allows to enter a name for a cognitive map; GRAPH $\longrightarrow$RELATION: It creates a relation from a cognitive map, GRAPH-DRAWING: It opens a submenu from which different graph algorithms can be chosen, particularly: LAYER which places the edges vertically; FOREST which draws a directed forest and WHOLISTIC-APPROACH which draws a particular *CM* that we will detail later in section 4.

3 *CMs* as a Tool for Qualitative Distributed Decision Making

CMs can also help an agent or a group of agents considered as a whole to make a decision. Given a cognitive map with one or more decision variables and a utility variable, which decision should be taken and which should be rejected? To achieve this, the concerned agent should calculate the total effect of each decision on the utility variable. Those decisions that have a $+$ or $\oplus$ total effect on utility should be chosen, and decisions that have a $-$ or $\ominus$ total effect should be rejected. Generally, no advice can be given about decisions with a, that is an ambivalent, total effect on utility, whereas that a $\pm$ or ? total effect on utility should not be rejected because it raises the undetermined decision problem. To solve such undeterminated decision, we propose here an original algorithm which is based on the principle of superposition adopted for *CMs*. This principle stipulates that the result of applying together two concepts C_1 and C_2 is the same as applying C_1 and C_2 *in sequence*.

Algorithm for solving the undetermined decision

1. For any concept C that has an undetermined result on the utility U, calculate all the indirect effects between C and U; then separate those indirect effects in positive and negative paths; i.e., paths with "+" and "−" total indirect effect respectively;
2. Cut off all the negative paths and evaluate the effect of positive paths on U, then note P_1 this evaluation;
3. Repeat the previous step for the effect of negative paths on U (without taking into account the positive paths) and note P_2 this evaluation;
4. Compare P_1 and P_2
    (a) if P_1 is more valuable than P_2 then the sign between C and U is "+";
    (b) else if P_1 is less valuable than P_2 then the sign between C and U is "−";
    (c) else if P_1 ia as valuable as P_2 then the sign between C and U is "0".

We will show below how this algorithm operates with a concrete example. Before that, we now illustrate the decision-making process in the context of multiagent environments using *CMs*. To achieve this, consider for example the causal map of a professor P_1 (considered as an agent) shown in Figure 6 who supervises a research group called G_{12}) and who has to choose between two courses D_1 and D_2 (D_1 and D_2 are decisions variables). The question now is how P_1 can choose between D_1 and D_2 knowing the facts reflected by the causal map, shown in Figure 6. This causal map includes the following P_1 beliefs. D_1 favors the theoretical knowledge of G_{12}'s students. Greater theoretical knowledge gives a greater motivation to students. Greater motivation of students gives a better quality of research for group G_{12}, which gives a greater utility of G_{12} which, in turn, has a positive result on utility of P_1. Finally, the second decision variable D_2 is an easy course that decreases the workload of P_1. Obviously, decreasing P_1's workload increases her utility.

In this case, how can P_1 make her choice between the two courses D_1 and D_2? Notice that in the context of our example, P_1 should reason about another agent which is the group G_{12} to make her decision. In other contexts, and for other decisions, she can also collaborate with her group to develop her decision. In this sense, the decision-making process considered here is a multiagent process. To run this process, it might be useful to convert the causal map being analyzed to the form of a valency matrix V. With the valency matrix, P_1 can calculate indirect paths of length 2 (i.e. V^2), 3 (i.e. V^3), etc., and the total effect matrix V_t. In fact, V_t tells P_1 how the decision variables D_1 and D_2 affect her utility and G_{12}'s utility. This gives the following matrix of size 2×2 (keeping only the relevant entries) involving two decision concepts (DC), D_1 and D_2, and two utilities considered as value concepts (VC), namely, Utilities of G_{12} and P_1.

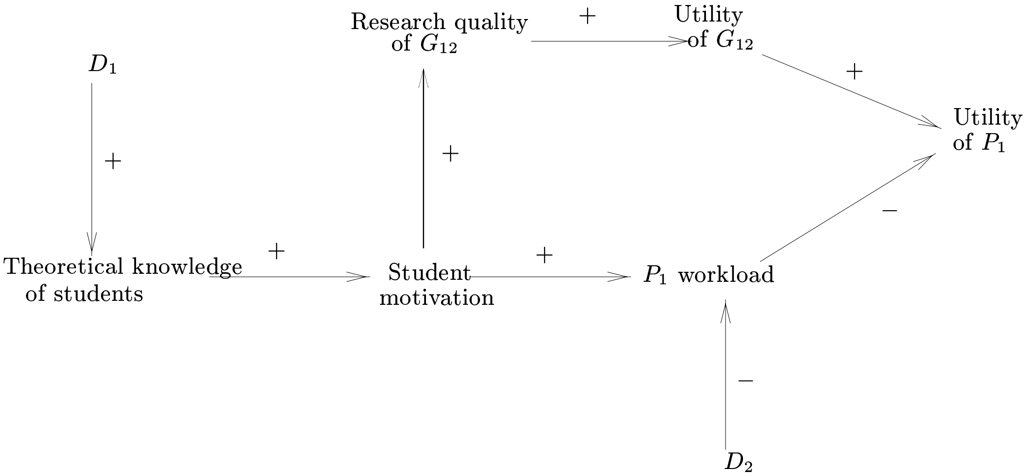


Figure 6: An illustrative example for decision-making in a multiagent Environment.

$DC \backslash VC$	Utility of G_{12}	Utility of P_1
D_1	+	?
D_2	−	+

Thus, P_1 perceives (1) decision D_1 as having a positive effect on Utility of G_{12} and an undetermined effect on her utility; (2) decision D_2 as having a negative effect on Utility of G_{12} and a positive effect on her utility. In these conditions, it is important to remove the undetermined result of D_1 decision on P_1 utility. To achieve this, we apply the previous algorithm as follows:

1. To see the impact of giving the course D_1 on utility of G_{12} we cut off the negative path produced by "Student motivation" —(+)—> "Workload of P_1" —(−)—> "Utility of P_1". Practically, this means that P_1 evaluates the following hypothetic situation: "if the course D_1 will be given by another colleague what will be the impact (I_1) of D_1 on my utility without taking into account the workload induced by D_1?"
2. Similarly, we cut off the positive path produced by "Student motivation" —(+)—> "Research quality of G_{12}" —(+)—> "Utility of G_{12}" —(+)—> "Utility of P_1". By doing so, we can see the impact (I_2) of giving the course D_1 on the workload ($W2$) of P_1 without the positive impact induced by the group G_{12}. Practically, this means that P_1 evaluates the following hypothetic situation: "What will be the impact (I_2) on my utility if I give the course D_1 to another group that has no connection with me?".
3. Finally, If the impact I_1 compensates I_2 then D_1 —(0)—> utility of P_1; (b) is more valuable than I_2 then D_1 —(+)—> utility of P_1; (c) is less valuable than I_2 then D_1 —(−)—> utility of P_1

Suppose that P_1 *believes* that the impact of giving the course D_1 produces effects on her utility, via her group of research, which are more valuables than what this course gives her as workload. In these conditions, we have

$DC\backslash VC$	Utility of G_{12}	Utility of P_1
D_1	$+$	$+$
D_2	0	$+$

It is clear here that decision D_1 would be preferred on decision D_2 because this decision has a positive impact on P_1's utility and on G_{12} utility. Conversely, D_2 has only limited impact because it only positively influences the utility of P_1.

How the CM-RELVIEW tool can be used by Decision Makers (DMs) for their QDM

Decision makers (DMs) can elicit causal knowledge about their decision and utility variables from different sources, including documents (such as corporate reports or memos), questionnaires, interviews, grids, and interaction and communication between other agents. After that, they use the relation editor of CM-RELVIEW for filling matrices relative to this causal knowledge. Then, they use the GRAPH button for transforming those matrices, into graphs (causal maps). Finally, they analyze those causal maps using the TRANS button.

Here, how a decision maker (DM) can use this tool. By pressing the button TRANS in the menu window (Fig. 2), CM-RELVIEW, a decision maker (DM) can calculate the transitive closure, (i.e., the total effect that a decision has on the utility variable). In the case where there is an undetermined result, CM-RELVIEW applies the algorithm introduced previously and asks the DM to give it some guidance to solve the undetermined result. In particular, the DM is asked to supply (1) the impact of positive and negative paths and, (2) the most valuable impact. A fully automated process for solving the undetermined result problem is scheduled in the agenda of our future work.

4 *CMs* as a Tool For Studying Changes in Organization of Agents

In multiagent systems, the study of an organization of agents has generally focused on some structural models such: (1) centralized and hierarchical organizations, (2) organizations as authority structure, (3) market-like organizations, (4) organizations as communities with rules of behavior. All these structures missed dynamic aspects and influences that exist in an organization of agents.

Weick [18] suggested to change the prevalent static view of an organization of agents to a dynamic view which is sustained by *change*. Precisely, he proposed that organization and change were two sides of the same social phenomena. His reasoning was that an organization is a process of co-evolution of agents' perceptions, cognitions and actions. In this context, Weick proposed a theory of organization and change based on the graphs of loops in evolving social systems. In the last decade, additional investigation guided by this approach [3, 4] tried to articulate how *CMs* provide a way to identify the loops that produce and control an organization.

As an example, consider the organization that binds researchers, grant agencies and qualified personnel in any (science and engineering) department. The causal map representing this organization is shown in Figure 7. The meaning of this *CM* is clear and we shall explain it no more.

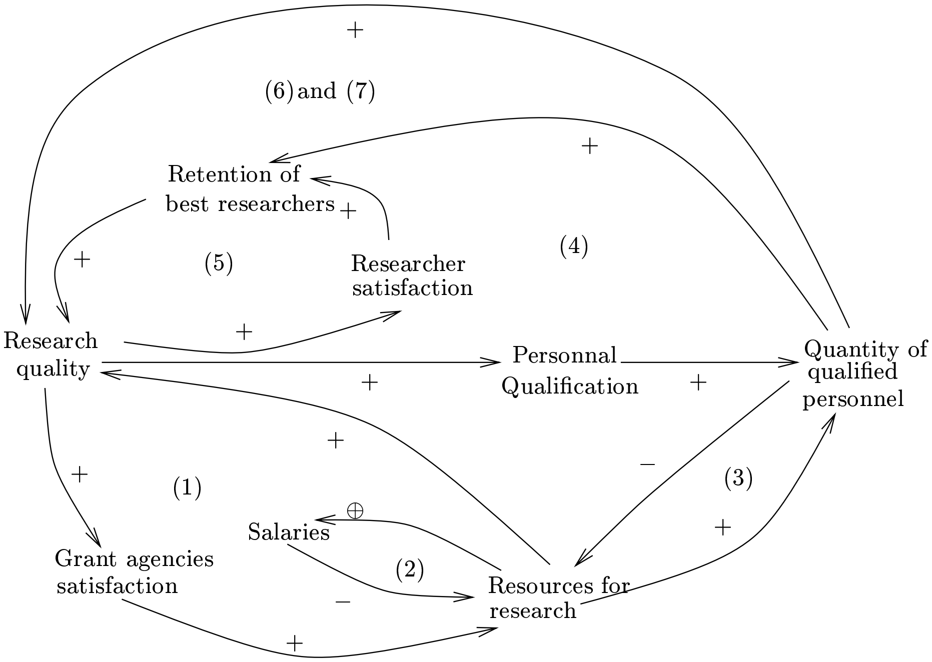


Figure 7: An organization of agents as loops.

In this causal map, concepts link together to form loops, some of which are numbered (1) to (7). Loops (1), (4)–(7) are *deviation-amplifying* loops. Change in the organization is the result of such loops, because any initial increase (or decrease) in any concept loops back to that concept as an additional increase (or decrease) which, in turn, leads to more increase (or decrease).

Loops (2) and (3) are *deviation-countering* loops [4]. The stability of the organization is the result of such loops. In the case of loop (2), for instance, an increase of resources for research can lead to an increase of salaries which, in turn, reduces the resources allowed to research. If this reduction is not enough to compensate the initial increase of resources, then a residual increase of salaries takes place which, in turn, reduces the resources, and so on, until a balance between the initial increase of resources and salaries is reached. Thus, deviation-countering loops are useful for stabilizing the growth generated in an organization.

Notice that in a wholistic approach the whole constraints the concepts and the relationships between them. With an organization of agents represented as a wholistic approach , we obtain a dynamic system in which deviation-amplifying loops are responsible for change and deviation-countering loops are responsible for stability of the organization. Using these loops, an individual strategist can direct strategic change in the desired directions. This can be achieved by 1) choosing and changing a loop or 2) choosing and changing a set of loops.

How the CM-RELVIEW Tool can be Used by DMs for the Reasoning on Organization Changes

Here also, DMs elicit causal knowledge about their organizations from different sources as reports, memos, questionnaires, interviews, etc.. After that, they use the CM-RELVIEW for constructing causal maps reflecting this causal knowledge. Finally, they use the CM-RELVIEW tool for analyzing those causal maps.

As stated in Section 2, the submenu of the graph menu called WHOLISTIC-APPROACH allows DMs to draw a “wholistic” causal map, whereas the menu WHOLISTIC-CM of TEST allows them to test it by choosing and changing a loop. Obviously, the loop to be changed should be a weak loop loosely coupled to the system. CM-RELVIEW offers DMs the following actions for changing a loop (from deviation amplifying to deviation countering, or vice versa): ADD-NODE: adding a node; REM-NODE: removing a node; REP-NODE: replacing a node; CHG-LABEL: changing the label of a link.

5 Conclusion and Future Work

We have firstly proposed a tool for qualitative reasoning based on cognitive maps representing relationships between agents’ beliefs. This tool allows users to determine certain quantitative and qualitative features of any cognitive map. Then, we have argued for the use of this tool in the context of multiagent systems, particularly for the reasoning on interrelationships among a set of individual and social concepts.

There are many directions in which the proposal made here can be extended.

- The full possibilities of relation algebra have yet to be exploited. Another option is to study “fuzzy relations” between agents’ concepts [20]. Our approach might be extended in this direction to take into account many degrees and vague degrees of influence between agents such as none, very little, sometimes, a lot, usually, more or less, and so forth [10, 14].
- Applications such as the following ones must be investigated in greater depth:
  1) negotiation and mediation between agents in the case of reasoning about subjective views;

2) knowledge available to or necessary to agents in the case of nested causal maps;
3) reasoning about the wholistic approach; and
4) reasoning on social laws, particularly for qualitative decision making.

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