

# Consensus determining algorithm in multiagent decision support system with taking into consideration improving agent's knowledge

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**Abstract**—This document describes using consensus methods to improve agent's knowledge in multiagent decision support systems. The problem of improving agent's knowledge, structure of decision, profile and criterions of consensus determining are presented in first part of article. Next a two stage algorithm of consensus determining was elaborated. This algorithm, among other things, allow to shorten the period of time necessary to take a decision, to limit the risk associated with this process and leads to increased effectiveness of decision taking since solutions generated by agents of inadequate level of knowledge are not taken into account.

## I. INTRODUCTION

The role of multiagent systems in supporting the decision making processes has increased. Characteristic features of modern economy, such as [8] globalization, the importance of knowledge, environmental turbulence, dynamicity of decisions, product personalization, approaching virtual reality, integration, or widely used digital technology and computer networks all present new challenges to the decision support systems. These challenges are for example:

- real time working,
- mobility in internet,
- getting suitable value information [12],
- skill in communication by elements of system,
- intelligence, ability to make conclusions,
- ability of acting itself on the basis of conclusions.

All the mentioned requirements have been satisfied by agent programs which make up the multiagent decision support system. Within the system each agent searches and reads data from the Internet after which follows the deduction process resulting in a decision. The system provides a decision maker with quick and up-to-date information, thanks to which the decision making process becomes more effective. However, to generate adequate decisions an agent has to have current knowledge of the surrounding world.

In the paper [7], it has been found that in order for a multiagent system to function properly, agents have to continuously improve their knowledge. The knowledge may be improved in a variety of methods. The paper [18] suggests a method which presupposes that the code of an agent's program contains monitoring procedures which verify whether an agent's knowledge is sufficient to his proper functioning. These procedures check the effectiveness of agent's actions

by monitoring results he produces. However, such a method has some flaws. Firstly, an agent who goes to any lengths to achieve his aim may overestimate his knowledge. Secondly, in case of malfunctioning agents, knowledge monitoring procedures may work inadequately which will result in inadequate knowledge condition. That is why, the paper [11] suggests a method which assumes that there are additional agents in the system which analyze the behavior of individual agents, and determine their current state of knowledge. Among numerous advantages of such an approach is the impartiality of knowledge assessment, and resistance to failures of individual agent programs.

Another solution contributing to improving agents' knowledge is the possibility of solving knowledge conflicts among agents. It is a common occurrence that in multiagent decision support system agents generates different versions of solutions, resulting in conflicts of agents' knowledge. Such situations may arise due to various reasons. Agents may use different sources of information, or they may employ different decision support methods. Knowledge conflicts concern situations in which different values are assigned by parties to a conflict to the same world objects and features [8]. It has been assumed of course that the conflicting parties' knowledge is described with the use of a certain set of features, i.e. using a given structure. This multivalued structure [3] in multiagent decision support systems is especially because agents, besides its decisions generate also degree of secure of these decisions. Detecting the conflict in such structures relies not only on comparison of value all attributes, but also on comparison of these structures contents, because they can consist of different attributes. If structures presented by parties to a conflict are different, or the values of attributes within structures are different, the result is a conflict of knowledge. Users, however, expect from the system the one version, in other words, the one decision. It is necessary, on the basis of various solutions, to select one which will satisfy users, and solve the knowledge conflict [1].

In various books on the subject, one may come across many methods of solving such conflicts. For example, paper [4] suggests an arbitration method in which a conflict is solved by the system itself, without the participation of agents. Paper [2], however, suggests using the method of negotiation between agents. Agents communicate between

themselves in order to establish and agree on a single, uniform state of knowledge. Negotiations, however, are time-consuming and result in slowing down the system's operation, which obviously affects the effectiveness of decision making.

Many papers, among other things [8, 15], suggest using consensus methods to solve knowledge conflicts. Such methods enable selecting one solution (in this case, a decision) among many alternatives. A decision selected with the use of consensus methods does not have to be one of the decisions generated by the system. It may just be very similar to them. In the consensus methods, every party is taken into account, every party to a conflict "loses" as little as possible, every party contributes to the consensus, all parties accept the consensus and the consensus is representative of all the parties to a conflict [16]. So far, determining a consensus, has most often taken place within a single stage (after generating a decision by individual agents). It must be noted, however, that knowledge of certain agents may often be insufficient to properly generate decisions (for example, it may be outdated, or incomplete), or the knowledge may be wrong as a result of some damage or improper operational algorithm of an agent. In a single-stage consensus determining process, decisions generated by such agents are taken into account along with decisions generated by properly functioning agents (every party to a conflict is taken into account). Such a situation may result in users receiving "worse" decisions. In order to solve this type of problem, a multi-stage consensus determining method may be used. The method has been defined in paper [8], however, it has not been employed in practical solutions yet.

The purpose of this article is elaborate algorithm of two-stage consensus determining allow to improving knowledge of agents, which functioning incorrect, and in consequence make decision support process more effective.

## II. CONSENSUS METHODS

The structure of decision representation is a set of decision elements which describe real world, e.g. suppliers, customers, products, etc. These elements (attributes) are ordered in sequence to proceeding during decision realisation. A formal definition of the structures presented in work [13]:

### Definition 1.

The structure decision  $P$  of finite set of decision elements  $E = \{e_1, e_2, \dots, e_Y\}$  is called as sequence:

$$P = \langle \{EW^+\}, \{EW^\pm\}, \{EW^-\}, Z, SP, DT \rangle,$$

where:

$$1) EW^+ = \langle e_o, pe_o \rangle, \langle e_q, pe_q \rangle, \dots, \langle e_p, pe_p \rangle;$$

couple  $\langle e_x, pe_x \rangle$ , where:  $e_x \in E$  and  $pe_x \in [0, 1]$ , denote a decision element and participation this element in set  $EW^+$ ; decision element  $e_x \in EW^+$  will be denoted by  $e_x^+$ ;

The set  $EW^+$  is called positive set, in other words it is a set of decision elements, about which the agent knows that these elements are in the environment.

$$2) EW^\pm = \langle e_r, pe_r \rangle, \langle e_s, pe_s \rangle, \dots, \langle e_t, pe_t \rangle;$$

couple  $\langle e_x, pe_x \rangle$ , where:  $e_x \in E$  and  $pe_x \in [0, 1]$ , denote a decision element and participation this element in set  $EW^\pm$ .

Decision elements  $e_x \in EW^\pm$  will be denoted by  $e_x^\pm$ .

The set  $EW^\pm$  is called neutral set, in other words it is set of decision elements, about which the agent does not know that these elements are in the environment.

$$3) EW^- = \langle e_u, pe_u \rangle, \langle e_v, pe_v \rangle, \dots, \langle e_w, pe_w \rangle.$$

Couple  $\langle e_x, pe_x \rangle$ , where:  $e_x \in E$  and  $pe_x \in [0, 1]$ , denote a decision element and participation this element in set  $EW^-$ .

Elementary objects  $e_x \in EW^-$  will be denoted by  $e_x^-$ .

The set  $EW^-$  is called a negative set, in other words it is a set of decision elements about which the agents knows that these elements are not in the environment.

$$4) Z \in [0, 1] - \text{rate of return in percent.}$$

$$5) SP \in [0, 1] - \text{degree of secure of rate } Z.$$

$$6) DT - \text{date of knowledge.}$$

Presented decision definition allows formulating system nodes conclusions in uniform structure. It can happen that an agent does not "know" whether a given element of decision can be used or not (for example agent has not got information about given value paper). So, set  $EW^\pm$  is necessary. Presented structure is complex and multivalued, there are different data types and multiattribute functional dependencies in this structure. The example of the structure is presented at table 1.

In the first example sets  $EW^+, EW^\pm, EW^- \neq \emptyset$ . In the second example set  $EW^\pm = \emptyset$ .

Situation, in which the structures of decision in the system differ, or the values of their attributes are different, is called an inconsistency in the state of knowledge of these agents. In this case consensus methods can be applied to coordinate the state of knowledge.

In literature of subject, consensus is defined as a resolution, which, is a compromise determined on the basis of existing resolutions. There are several phases of finding consensus. First, the exact structure of set decision generated by agents must be specified. Next, the distance between these decisions is calculated. Finding consensus is choosing such decision, for which the distance between this decision (consensus) and decisions generated by agents is minimal (according different criterions).

The outcome of consensus method application is a good representation of the set of decisions, because it takes into consideration practically all the subsets of the set. Set of

TABLE I.  
EXAMPLE OF THE STRUCTURE

Let set  $E = \{a_1, a_2, a_3, a_4, a_5\}$ .

Examples of structure of knowledge:

$$D1 = \{\langle a_1, 0.2 \rangle, \langle a_3, 0.5 \rangle, \langle a_5, 0.3 \rangle, \langle a_2, 1 \rangle, \langle a_4, 1 \rangle, 0.3, 0.7, 22-09-2012\}$$

$$D2 = \{\langle a_2, 0.2 \rangle, \langle a_3, 0.8 \rangle, \{\emptyset\}, \langle a_1, 1 \rangle, \langle a_4, 1 \rangle, \langle a_5, 1 \rangle, 0.6, 0.3, 14-05-2012\}$$

such decisions we called a profile and defined as follow [15]:

**Definition 2.**

Set of decision elements  $E = \{e_1, e_2, \dots, e_Y\}$  is given.

A profile  $A = \{A^{(1)}, A^{(2)}, \dots, A^{(M)}\}$  is called set of  $M$  decisions of finite set of decision elements  $E$ , such that:

$$A^{(1)} = \{\langle EW^+ \rangle^{(1)}, \langle EW^\pm \rangle^{(1)}, \langle EW^- \rangle^{(1)}, Z^{(1)}, SP^{(1)}, DT^{(1)}\}$$

$$A^{(2)} = \{\langle EW^+ \rangle^{(2)}, \langle EW^\pm \rangle^{(2)}, \langle EW^- \rangle^{(2)}, Z^{(2)}, SP^{(2)}, DT^{(2)}\}$$

⋮  
⋮  
⋮

$$A^{(M)} = \{\langle EW^+ \rangle^{(M)}, \langle EW^\pm \rangle^{(M)}, \langle EW^- \rangle^{(M)}, Z^{(M)}, SP^{(M)}, DT^{(M)}\}$$

In different works [5, 6, 16], different kinds of criterions of determining consensus are presented. For example, a minimal sum of distance between consensus and profile was taken into consideration (it is called as consensus according to criterion  $C_1$ ). Such consensus is very similar to one of profile elements. A minimal sum of square of distance between consensus and profile is also use as distance measure (consensus according criterion  $C_2$ ). Such consensus is more even that is equal extent near to all profile elements. In consequence decision determined by consensus equal extent all part of conflicts is taking into consideration.

In follow part of article the two-stage consensus determining algorithm will be elaborate. In such proceed it is possible to use criterions  $C_1$  and  $C_2$  in the same time depending on system user preferences.

### III. TWO-STAGE CONSENSUS DETERMINING ALGORITHM

Two-stage consensus determining allows to elimination a decisions generated by agent programs, which knowledge state is incorrect, well it is possible, that their decisions are also incorrect. By means of that, it was eliminate influence of incorrect decision to final decision, which is determine by use consensus methods and presented user.

In conception of two-stage consensus determining (figure 1) it assume determining consensus in first stage (for example according criterion  $C_1$ ) on the basis of decisions generated by each agent, which is working in the system, that is initial set of agents (decisions profile). Next, evaluation of decision all of agents is achieving. This evaluation can be achieve for example by evaluation agent (so, method

described in paper [11] is used) in this way, that decisions most remote from consensus (by means of distance) get the worst evaluations, and decisions nearest consensus get the best evaluation. Next, agents, which decisions got the worst evaluations are eliminated and set of agents (decisions profile) after evaluation is created. On the basis of these agents decisions in the second stage consensus is determining (for example according criterion  $C_2$ ) and decision determined in this stage is presented to user.

It can be used a theorem defined in work [8, 16] to determine two-stage consensus in the multiagent decision support system.

In this algorithm, for each decision element in set  $E$  it is checking, how many times did this element in set  $EW^+$ ,  $EW^\pm$  and  $EW^-$ . If the element appeared in one of the sets more times than  $\frac{1}{2}$  of the number of all agents, it belongs to this set in consensus. If it appeared in given set as often as  $\frac{1}{2}$  of number of all agents or less often than  $\frac{1}{2}$  of the number of all agents, it does not belong to the consensus.

If a given decision element belongs to a given set in the consensus, we move to another element of set  $E$ .

Next, we determine an ascending order of values  $Z$ ,  $SP$ ,  $DT$  for the whole profile and estimate where, between the values in these orders have to be the value that represents consensus. The algorithm is done, when all the elementary objects have been checked and the consensus for a  $DT$  value has been found.

In next stage, evaluation a decisions generated by agents and elimination agents, with incorrect knowledge state, is achieving. The set of agents after evaluation is creating (in this set there are agents witch correct knowledge state). Decision of this agents produce a profile, and on the basis of this profile a second-stage consensus is determining (according to criterion  $C_2$ ).

To determining such consensus first, on the basis of profile after evaluation, a consensus according to criterion  $C_1$  is determining, and square of distance between consensus and profile is calculate and this consensus is take on minimal.

Next, for each element of set  $E$ , it is checked, if it is appear in given set in consensus. If it is then it is eliminate from this set and square of distance is calculated. If this square of distance is greatest then previous then go to next set, if it is lesser then it is take on consensus and distance between this consensus and profile as minimal.

If the element is not appear in given set in consensus, then it is calculate how many times it appears in this set in

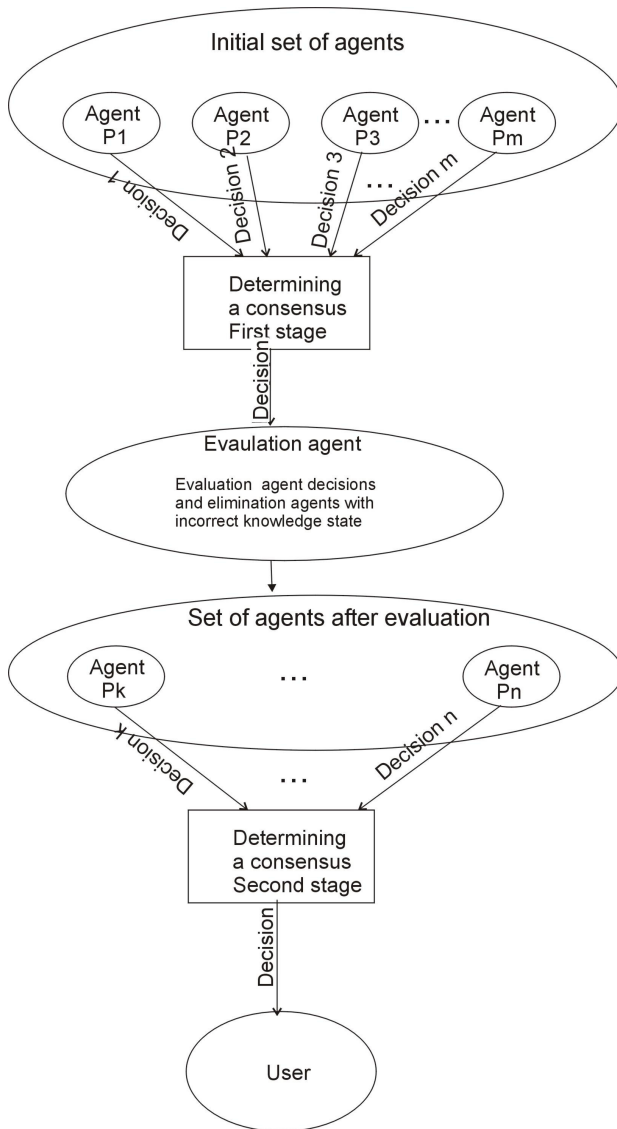


Fig. 1 Conception of two-stage consensus determining.

decisions of profile. If it is not any time then go to next set, if it is appear once or more times then it is additional to this set (if necessary it is eliminated with other set) and it is checked if distance between new consensus and profile is lesser than previous. If it is not, then previous consensus is take on the best, if it is, then new consensus is take on the best and distance between this consensus and profile as minimal.

After check each of sets it goes to next element of set  $E$ .

If each of elements of set  $E$  will be checked then it is take on that consensus of set  $EW^+$ ,  $EW^\pm$ ,  $EW^-$  is determined and next will be determine a consensus of  $Z$ ,  $SP$  and  $DT$ . After determine this consensus the algorithm is finished and receive consensus is a double-stage consensus. This algorithm is defined as follow:

**Data:** Profile  $A = \{A^{(1)}, A^{(2)}, \dots, A^{(M)}\}$  consist of  $M$  knowledge structure of agent.

**Result:** Consensus

$$CON = \langle CON_+, CON_\pm, CON_-, CON_{DT} \rangle$$

consideration for  $A$ .

**BEGIN**

**Step 1:**  $CON_+ = CON_\pm = CON_- = \emptyset$ ,

$$CON_Z = 0, CON_{SP} = 0, CON_{DT} = 0$$

**Step 2:**  $j := 1$ .

**Step 3:**  $i := +$ .

**Step 4:** If  $t_i(j) > M/2$  then  $CON_i := CON_i \cup \{e_j\}$ . Go to: Step 6.

**Step 5:** If  $i = +$  then  $i := \pm$ . If  $i = \pm$  then  $i := -$ . If  $i = -$  then go to: Step 6.

Go to: Step 4.

**Step 6:** If  $j < Y$  then  $j := j + 1$ . Go to: Step 3.

If  $j \geq Y$  then go to: Step 7.

**Step 7:**  $i := Z$ .

**Step 8:** Calculate  $pr(i)$ .

$$\text{Step 9: } k_i^1 = (M + 1) / 2, k_i^2 = (M + 2) / 2.$$

$$\text{Step 10: } k_i^1 \leq CON_i \leq k_i^2.$$

**Step 7:**  $i := SP$ .

**Step 8:** Calculate  $pr(i)$ .

$$\text{Step 9: } k_i^1 = (M + 1) / 2, k_i^2 = (M + 2) / 2.$$

$$\text{Step 10: } k_i^1 \leq CON_i \leq k_i^2.$$

**Step 7:**  $i := DT$ .

**Step 8:** Calculate  $pr(i)$ .

$$\text{Step 9: } k_i^1 = (M + 1) / 2, k_i^2 = (M + 2) / 2.$$

$$\text{Step 10: } k_i^1 \leq CON_i \leq k_i^2.$$

**Step 11:** Evaluation of decision and elimination of agent with have incorrect knowledge state.

**Step 12:** Calculate a profile

$B = \{B^{(1)}, B^{(2)}, \dots, B^{(N)}\}$  consist of  $N$  decisions.

**Step 13:** Let  $CON$  is a consensus according criterion  $C_1$ .

$$\text{Step 14: } CON_Z = \frac{1}{N} \sum_{i=1}^N Z^i.$$

$$\text{Step 15: } CON_{SP} = \frac{1}{N} \sum_{i=1}^N SP^i.$$

$$\text{Step 16: } CON_{DT} = \frac{1}{N} \sum_{i=1}^N DT^i \text{ let}$$

$$d := \sum_{i=1}^N \left[ \Psi(CON, A^{(i)}) \right]^2 \quad \text{and } j := 1.$$

**Step 17:** If  $e_j \in CON_+$  then  $CON' := \langle CON_+ \setminus \{e_j\}, CON_\pm, CON_-, CON_Z, CON_{SP}, CON_{DT} \rangle$

Go to: Step 20,

If  $e_j \notin CON_+$  then go to: Step 18.

**Step 18:** If  $t_+(j) = 0$  then go to: Step 21,

If  $t_+(j) > 0$  then go to: Step 19.

**Step 19:** If  $e_j \cap CON \neq \emptyset$  and  $e_j \in CON_{\pm}$  or  $e_j \in CON_{\pm}$  then

$CON' :=$

$\langle CON_+ \cup \{e_j\}, CON_{\pm} \setminus \{e_j\}, CON_- \setminus \{e_j\}, CON_Z, CON_{SP}, CON_{DT} \rangle$

If  $e_j \cap CON = \emptyset$  then

$CON' :=$

$\langle CON_+ \cup \{e_j\}, CON_{\pm}, CON_-, CON_Z, CON_{SP}, CON_{DT} \rangle$

Go to: Step 20.

**Step 20:** If  $\sum_{i=1}^N [\Psi(CON', A^{(i)})]^2 < d$  then  $d :=$

$\sum_{i=1}^N [\Psi(CON', A^{(i)})]^2$  and  $CON := CON'$

Go to: Step 21.

**Step 21:** If  $e_j \in CON_{\pm}$  then  $CON' :=$   
 $\langle CON_+, CON_{\pm} \setminus \{e_j\}, CON_-, CON_Z, CON_{SP}, CON_{DT} \rangle$

Go to: Step 24,

If  $e_j \notin CON_{\pm}$  then go to: Step 22.

**Step 22:** If  $t_{\pm}(j) = 0$  then go to: Step 25,

If  $t_{\pm}(j) > 0$  then go to: Step 23.

**Step 23:** If  $e_j \cap CON \neq \emptyset$  and  $e_j \in CON_+$  or  $e_j \in CON_-$  then

$CON' :=$

$\langle CON_+ \setminus \{e_j\}, CON_{\pm} \cup \{e_j\}, CON_- \setminus \{e_j\}, CON_Z, CON_{SP}, CON_{DT} \rangle$

If  $e_j \cap CON = \emptyset$  then

$CON' :=$

$\langle CON_+, CON_{\pm} \cup \{e_j\}, CON_-, CON_Z, CON_{SP}, CON_{DT} \rangle$

Go to: Step 24.

**Step 24:** If  $\sum_{i=1}^N [\Psi(CON', A^{(i)})]^2 < d$  then  $d :=$

$\sum_{i=1}^N [\Psi(CON', A^{(i)})]^2$  and  $CON := CON'$ .

Go to: Step 25.

**Step 25:** If  $e_j \in CON$  then  $CON' :=$

$\langle CON_+, CON_{\pm}, CON_- \setminus \{e_j\}, CON_Z, CON_{SP}, CON_{DT} \rangle$

Go to: Step 28.

If  $e_j \notin CON$  then go to: Step 14.

**Step 26:** If  $t(j) = 0$  then go to: Step 29.

If  $t(j) > 0$  then go to: Step 27.

**Step 27:** If  $e_j \cap CON \neq \emptyset$  and  $e_j \in CON_+$  or  $e_j \in CON_{\pm}$  then

$CON' :=$

$\langle CON_+ \setminus \{e_j\}, CON_{\pm} \setminus \{e_j\}, CON_- \cup \{e_j\}, CON_Z, CON_{SP}, CON_{DT} \rangle$

If  $e_j \cap CON = \emptyset$  then

$CON' :=$

$\langle CON_+, CON_{\pm}, CON_- \cup \{e_j\}, CON_Z, CON_{SP}, CON_{DT} \rangle$

Go to: Step 28.

**Step 28:** If  $\sum_{i=1}^N [\Psi(CON', A^{(i)})]^2 < d$  then  $d :=$

$\sum_{i=1}^N [\Psi(CON', A^{(i)})]^2$  and  $CON := CON'$ .

Go to: Step 29.

**Step 29:** If  $j < Y$  then  $j := j + 1$ . Go to: Step 14.

If  $j \geq Y$  then END.

END.

Calculation complexity of this algorithm is  $O(N^2M) + O(3NM)$ .

Let's notice, that in second stage, determining consensus according criterion  $C_2$  is a NP-complete problem, therefore above algorithm is a heuristic algorithm.

Presented algorithm of two-stage consensus determining allow to coordinate a decision presented by system to user, with take into consideration improving knowledge of agents, which function in the system. Elaborated algorithm can be implemented in any multiagent decision support system under condition representation agent knowledge by structure described in this article. Algorithm is run automatically after generate proposition of decisions by agents.

Using this algorithm in a decision support system allow to more effective a supporting decision taking process, because several results are take into consideration. In multiagent decision support systems these results (decisions) are generated by different agents. Different kinds of decision support methods are implements in these agents. Of course decision maker can choose himself a decision presented by agents, but it is time-consuming process. So, using consensus methods considerably shorten time of taking decision and in consequence it contribute to better organization functioning.

#### IV. CONCLUSION

Improving agents' knowledge is an essential element of multiagent decision support systems' operation. One of the aspects of improving knowledge is solving knowledge conflicts within almost every system of that type. Designers of multiagent systems shall bear in mind that methods of recognition, classification, and solving conflicts should be taken into account already in the design phase. It may be extremely difficult to include them once the system has been implemented, due to changes in the code of agent programs. Proper solution of the conflicts is essential because it guarantees that the system will suggest proper decisions. If the mentioned aspects are disregarded at the system, then user (decision makers) may have problems with taking right and quick decisions because the system may suggest wrong decisions, or several decisions, which may result in the decision maker's wondering which one to chose.

Solving knowledge conflicts is possible also thanks to the use of the consensus methods, and the multistage consensus determining process, including the two-stage algorithm described in the article, enable more effective improvement of knowledge. Such an approach enables providing users with a decision which has been selected on the basis of decisions generated by agents possessing adequate knowledge. Agents whose level of knowledge is inappropriate at a given stage are not taken into account in the final consensus, however, they do have a chance of improving their knowledge, and consequently may be taken into consideration while determining a consensus in selecting further decisions. Thanks to such an approach, the risk that a decision presented to a user is faulty is decreased, and decision makers gain greater confidence that a decision suggested by a system using proper knowledge of agents is effective. The paper [15] points out that the use of consensus methods to solve knowledge conflicts, among other things, allows to shorten the period of time necessary to take a decision and to limit the risk associated with this process. The use of two-stage algorithm for determining consensus additionally leads to increased effectiveness of decision taking since solutions generated by agents of inadequate level of knowledge are not taken into account.

Of course, result of consensus algorithm did not ensure that the decision will be optimal, but it is worth stressing that since selected decisions are of certain usefulness for users, thanks to multistage consensus determining process, it is possible to "raise the bar" so as to increase the usefulness even more. Consequently, it may lead to reaping more benefits by organizations, or investors in the form of higher profits or more effective operation on competitive markets.

Further research purpose relating to improving agents knowledge with use multi-stage consensus determining shall depend on for example take into consideration greatest number of stages consensus determining and research its influence on effectively decision presented to user, elaborate of mechanism self-evaluation by agent its knowledge state or appoint different, than distance, criterions of evaluation agent's knowledge state. It is necessary also to verify this algorithm in practice.

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