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UNDERSTANDING COLLECTIVE INTELLIGENCE – A LITERATURE REVIEW FROM AN ENGINEERING PERSPECTIVE

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Abstract: As human beings are so tightly connected in social networks, and their evolution is so much determined by cultural factors, it can be argued that all the processes commonly called "intelligence" are in fact the result of social interactions. In other words, mind is a social phenomenon. Under these circumstances, the shallowness of the research on "collective intelligence" is quite surprising. Even the definition of the term seems affected by confusion and lack of consensus. This paper contains a brief review of the literature aimed to identify the relevant pieces of knowledge on collective intelligence and related concepts, with a special emphasis on the applications of the ICT for enabling and harnessing the wisdom of crowds. In the end, we propose a new definition of collective intelligence.

Keywords: collective intelligence, swarm intelligence, crowdsourcing, wisdom of crowds, emergence, human stigmergy

1. CONFUSION AND LACK ON CONSENSUS REGARDING THE DEFINITION OF COLLECTIVE INTELLIGENCE

A simple search on Google Scholar with the key "collective intelligence" returned (March 2016) 53,000 results. A similar search on "artificial intelligence" returned 1,890,000 results. One might believe that this huge difference is due to the fact that collective intelligence (CI) is a recent, "hot" topic, but this is not true, because the landmark paper that coined the term *"wisdom of crowds"* is dated more than a century ago (Galton, 1907).

Despite the obvious fact that some of the most successful ventures of all times (Google, eBay, Amazon, Facebook, etc.) owe their success to certain solutions for aggregating the wisdom of crowds, it appears that we are more interested in designing systems capable of (rather primitive) artificial intelligence, than in understanding our own (amazing) collective intelligence.

The web2.0 and the mobile applications give people unprecedented means to communicate and participate in collective endeavors, and in just a few years a plethora of new applications of the CI hit the market (think of reCAPTCHA, Quirky, Uber, Threadless, Waze, AirBnb, and Trip Advisor, to name just a few).

In contrast with the dynamics of the market, the scholar research on CI is still affected by confusion and lack of consensus.

For example, Bonabeau (in Bonabeau, 1999) defines the swarm intelligence (SI) as: "the emergent *collective intelligence* of groups of simple agents."

Salminen (in Salminen, 2012) states that: "I will use [the term] swarm intelligence to refer to the emergent, collective behavior of groups of cognitively simple agents such as insects, robots and simulation algorithms. The term collective intelligence is reserved for phenomena involving agents with high cognitive capabilities, namely humans. "

Krause et al. (2010) found no difference between the two terms: "the terminology in the literature can be confusing and different names are applied: such as SI [swarm intelligence], collective intelligence and collective cognition. *We consider these all to be essentially the same phenomena*, and refer to them as SI."

On a different position, Atlee and Por (2000) argue that: "this swarming behavior does not constitute collective intelligence per se, as it lacks awareness and intentionality." (see figure 1).

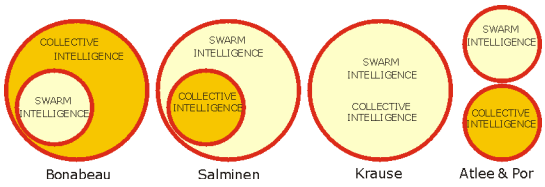

Fig.1. Various perspectives on the relation between SI and CI found in literature

Sometimes, the same researchers seem to change their minds about the definition of CI. For example, Levy (1997) thinks that: "collective intelligence is a form of universal, distributed intelligence, which arises from the collaboration and competition of many individuals".

Later (in Levy, 2010), he restricts the definition to human agents: "Collective intelligence (CI) is the capacity of *human collectives* to engage in intellectual cooperation in order to create, innovate and invent [....]. It can be applied at any scale, from work teams to huge networks or even to our whole species."

While some researchers seem to assimilate CI with simple conscious cooperation (e.g. Heylighen, 2013 who states that: "collective intelligence can be understood as the capacity of a group of people to collaborate in order to achieve goals in a complex context") , other focus on the emergence resulting from the indirect coordination through the actions on a shared environment and analyze the factors involved in "human stigmergy" (e.g. Susnea et al, 2013 and Susnea, 2015a).

Finally, Lykourentzou et al. (2011) emphasize the importance of the technology as enabler of CI: "any situation where large enough groups of people gather, act individually but also share some common community goals could potentially be – through the proper use of technology – transformed into a CI system."

This approach is pretty close to the main research objective formulated by the MIT Center for Collective Intelligence (http://cci.mit.edu/): "[find the means that] people and computers be connected so that – collectively – they act more intelligently than any individuals, groups, or computers have ever done before."

The landscape becomes even more complex if we consider several related concepts such as: crowdsourcing, social computing, folksonomy, collaborative filtering, social tagging, etc.

By reading the above listed definitions of the CI, it becomes obvious that they don't tell much about the nature of these phenomena. Neither do they tell us why sometimes the influence of the group is positive (collective intelligence, "wisdom of the crowd"), while in many other cases the influence of the group is negative ("collective stupidity", "madness of the crowd", "groupthing"), as compared with the individual performances of the group members.

These are in fact the research questions we are trying to answer in this study. The following section is an attempt to gain an insight into the nature of CI.

2. A CLOSER LOOK AT THE NATURE OF CI

Back in 1907, while visiting an animal fair, Sir Francis Galton stumbled upon a competition wherein 800 participants attempted to guess the weight of an ox (Galton, 1907). Though some of the 800 competitors were farmers or butchers, most of them were non-experts in evaluating the livestock. Each participant submitted an individual guess without interacting with the other members of the group.

Rather suprisingly, the average of the estimates of the entire group was better than any individual guess and differed by only one pound from the real weight of the ox. This "wisdom of the crowd" (see also Surowiecki, 2005) was seen by Galton as an argument in favor of the principles of democracy.

In fact, this simple form of collective intelligence is related to the technique of using multiple estimates to improve the precision of measurements (see figure 2).

It is important to note that in this type of CI, the members of the group do not interact with each other – a distinct instance performs the aggregation of the individual guesses, to produce a single global

estimate for the group (e.g. by computing the average). Moreover, as Lorenz et al. demonstrated (Lorentz et al, 2011), even minor social interactions within the group may severely undermine the overall performance of the group.

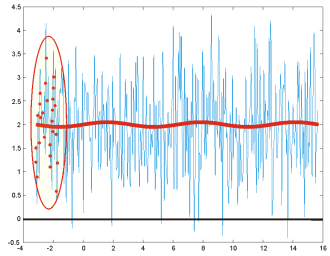

Fig.2. The mechanism that explains the wisdom of crowds: averaging multiple measurements may reduce the influence of the noise or other perturbing factors.

Apart from the condition regarding the independence of opinions of the participants, Krause et al. (2011) enumerate several other conditions for the accuracy of group estimates:

- diversity of opinions
- an incentive to motivate the participants to provide truthful reporting
- absence of a systematic bias

We should note that if any of the above conditions is not rigorously fulfilled, the collective intelligence dramatically drops and becomes "collective stupidity", or "groupthink" (see also Lorenz at al, 2011, and Janis, 1971).

A variety of solutions that rely on social media to aggregate the crowd provided estimates for *predicting future events* have been developed. Yu & Kak (2012) surveyed some of these solutions, and identified the following domains of applications:

- Movie box-office
- Information dissemination
- Elections
- Macroeconomic
- Miscellanea

For example, Lica & Tuta (2011) describe a means to aggregate the estimates of the crowd to predict the Oscar winning movies, by computing and comparing a "sentiments index" starting from the number of Twitter messages tagged as "positive", "negative" and "neutral":

$$I_{sent} = 100 * \frac{1 + (NR_{+} - NR_{-})}{2 * TotalMes} \quad (1)$$

where:

Isent – The sentiments index
NR_{+} - Number of positive messages
NR_{-} - Number of negative messages
TotalMes - Total number of messages, positive, negative, and neutral

In a similar, but more ambitious study, Bollen et al. (2011) attempted to predict the stock market evolution starting from the Twitter messages.

However, sending a Twitter message that express a certain sentiment towards a product, person or fact is just a particular facet of what has been called "Behavioral Implicit Communication - BIC" (see Omicini et al, 2004).

This moves the focus from the simplest type of CI, where the group members do not interact with each other (as in the experiment described by Galton) to another type of CI wherein the "agents" indirectly coordinate their actions by leaving traces in a shared environment, and sensing the traces left by other agents (see figure 3). Thus, the environment acts as a shared memory for the entire group of agents.

This indirect coordination mechanism was called "stigmergy" (Grasse, 1959) and raised a great interest as one of the core mechanisms that explain the self organization in systems composed of simple agents like insects or small robots.

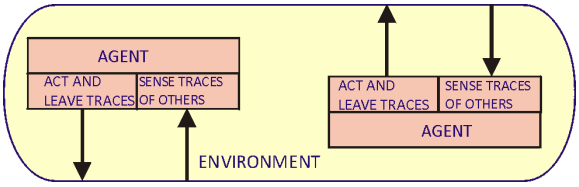

Fig.3. Stigmergy - The indirect coordination by means of traces left in the environment

The emergence of apparently intelligent behavior in swarms of simple agents was called "swarm intelligence" (Bonabeau, 1999; Eberhart et al., 2001).

Stigmergic interactions are possible (and sometimes desirable) in groups of human agents. We discussed the mechanisms and some possible applications of "human stigmergy" in (Susnea, 2012; Susnea et al. 2013; Susnea, 2015a), and we proposed a generic model of ICT mediated interactions in (Susnea, 2015b).

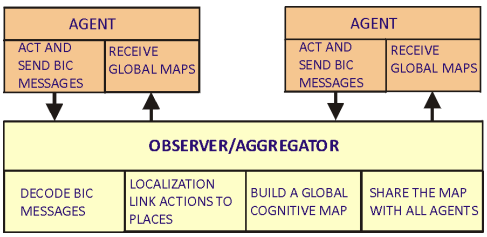

Fig.4. A model of the ICT mediated interactions in human stigmergy systems

According to this model, the CI processes can be triggered by creating a technological mediator ("observer") that aggregates the agent generated BIC messages into a global "cognitive map" of the environment, which is then shared with the agents.

Starting from the above listed examples, we can derive a simple taxonomy of the CI, by considering the degree of interactions between the agents within the group (see figure 5).

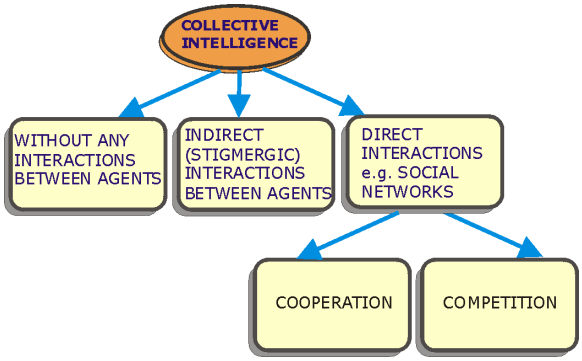

Fig.5. A simple taxonomy of CI starting from the degree of interactions between the participating agents

Though very simple, the taxonomy proposed in figure 5 brings some important clarifications:

- It eliminates some of the confusion regarding the definition of CI. It becomes clear that stigmergy can and should be considered a particular type of CI;
- Groups of non-human agents (animal, robotic, or virtual agents) can also exhibit CI. However, for the sake of uniformity with the literature, we agree with Salminen (2012) in what concerns the idea of using the term CI mainly for systems with human agents, while reserving the term "swarm intelligence" for the other types of agents.
- Intentionality and awareness are not mandatory requirements for CI. "Dumb" individual agents like ants or bees may participate in awesome CI systems.

A more elaborate and detailed analysis of the processes associated with CI is performed in (Malone et al., 2009). Here, the MIT experts describe a so called "genome" of the CI, where they identify the following "genes": the actors/agents, their motivation, the goals, and the processes.

A brief visual description of these factors is presented in figures 6, 7, 8 and 9. Note that the authors assume that CI involves exclusively human agents.

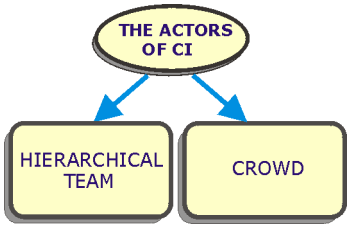

Fig.6. The "actors" involved in CI. Note the difference between "team" and "crowd"

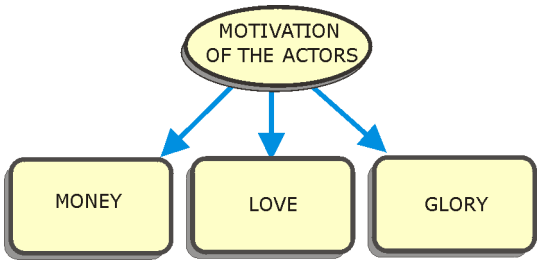

Fig.7. The motivation for participating in CI groups.

Note that this approach totally excludes the situations when the agents are unaware of their participation in a CI system (see the examples in Susnea 2015a, 2015b, 2016)

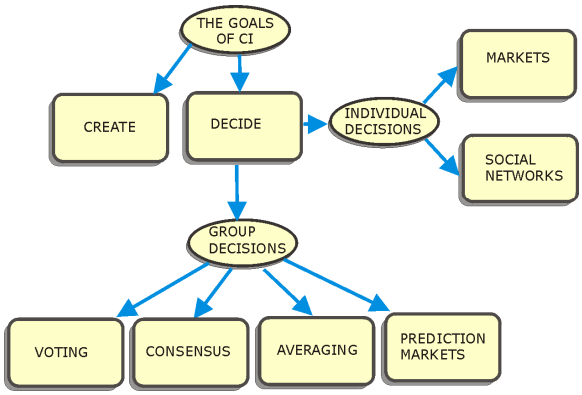

Fig.8. The goals usually found in CI applications

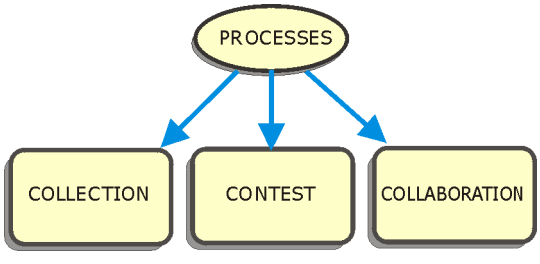

Fig.9. The processes involved in CI (apud Malone et al, 2009)

It is also important to note that, even the simplest forms of CI (like the example of the group estimating the weight of an ox, reported by Galton) assume the existence of an instance that "aggregates" the information provided by, or the results of the activity of the agents. Sometimes the aggregation is performed by the environment shared by the agents (as in stigmergy), in other cases complex technological means (e.g. computers and communication equipments) are involved (as in social networks).

The actual result of the aggregation may be the simple average of the individual estimates (as in the example cited by Galton), or some more complex processing may be required (as in the example of the sentiment index described in Lica & Tuta, 2011).

We believe that the actual implementation and complexity of the *aggregator* is the decisive factor that determines the value of the entire resulting CI system. *Here is where the emergence from individual to collective intelligence occurs*.

The above presentation of the main topics related to collective intelligence found in the literature is far from being exhaustive. It is only intended to clarify some terms and to give an insight on the nature of the processes involved in CI.

We will conclude this presentation by providing, in the next paragraph, several definitions of terms related or connected with CI.

3. RELATED CONCEPTS

3.1. Crowdsourcing

According the well known definition of Howe (http://crowdsourcing.typepad.com), "crowdsourcing is the act of taking a job traditionally performed by a designated agent (usually an employee) and outsourcing it to an undefined, generally large group of people in the form of an open call."

Defined this way, crowsourcing does not automatically produce CI, but it creates the conditions for the emergence of CI, by involving a (large) group of diverse agents.

See also Estelles-Arolas & Gonzales de Guevara (2012) for an in depth presentation of the various meanings of the term found in the literature.

3.2. Social computing

Parameswaran & Whinston (2007) define social computing as "…applications and services that facilitate collective action and social interaction online with rich exchange of multimedia information and evolution of aggregate knowledge…"

See also (Dryer et al., 1999).

3.3. Emergence

In a very general sense, emergence is the key element that makes complex systems irreducible to their parts.

It results that emergence is *always* associated with collective intelligence.

See (Corning, 2002) and (Deguet et al, 2006) for a review of the multiple definitions of the emergence.

4. DISCUSSION AND CONCLUSIONS

After reviewing some of the vast literature dedicated to collective intelligence, we are now capable to propose a new definition of this concept.

Here it is: "Collective intelligence is the totality of processes that lead to the emergence of either new knowledge, or intelligent decisions or behavior, within a group of agents coupled by sharing a common memory, or any other means to record and process information about the activity of the group."

Compared with the other, already cited definitions, this one seems more *comprehensive* (it covers systems comprising all kinds of agents, including virtual agents like those used in multi agent modeling and simulations), and *explanatory* (it introduces the concept of "coupling" between the agents as a condition for the emergence).

Another contribution of this paper is that it provides a selection of references to the most significant articles that can help someone trying to gain a deeper insight in the field – complex by nature – of the collective intelligence.

To conclude, we must agree with (Schut, 2010) who states that the research in collective intelligence is still in its infancy, and that we still need a theory capable to explain how CI actually works.

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