

# Collective Intelligence System Engineering

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## ABSTRACT

Collective intelligence (CI) is an emerging research field which aims at combining human and machine intelligence, to improve community processes usually performed by large groups. CI systems may be collaborative, like Wikipedia, or competitive, like a number of recently established problem-solving companies that attempt to find solutions to difficult R&D or marketing problems drawing on the competition among web users. The benefits that CI systems earn user communities, combined with the fact that they share a number of basic common characteristics, open up the prospect for the design of a general methodology that will allow the efficient development and evaluation of CI. In the present work, an attempt is made to establish the analytical foundations and main challenges for the design and construction of a generic collective intelligence system. First, collective intelligence systems are categorized into active and passive and specific examples of each category are provided. Then, the basic modeling framework of CI systems is described. This includes concepts such as the set of possible user actions, the CI system state and the individual and community objectives. Additional functions, which estimate the expected user actions, the future state of the system, as well as the level of objective fulfillment, are also established. In addition, certain key issues that need to be considered prior to system launch are also described. The proposed framework is expected to promote efficient CI design, so that the benefit gained by the community and the individuals through the use of CI systems, will be maximized.

## Categories and Subject Descriptors

H.1 [Models and Principles]: User/Machine Systems

## General Terms

Design, Standardization

## Keywords

Collective intelligence, system engineering

## 1. INTRODUCTION

Collective intelligence (CI) is one of the great challenges of our times. It is based on the concept that large groups of cooperating individuals can produce higher-order intelligence, solutions and innovation and come to function as a single entity.

Collective intelligence may receive various forms including volunteers that collaborate in order to achieve a common goal that will benefit their community, political parties that mobilize large numbers of people to run campaigns and select candidates, as well as large groups of individuals that collaborate or compete towards finding the best solution to a problem.

From the above one may observe that CI may generally exist without the use of technology. However, technological means, and especially the use of the internet, may help human communities evolve their collective capabilities in an unprecedented way and this is where collective intelligence systems especially come to place. The long term vision of CI systems is to fuse the knowledge, experience and expertise residing in the minds of individuals, in order to elevate, through machine facilitation, the optimal information and decisions that will lead to the benefit of the whole community [14]. Thus, through the combination of the best aspects of human and machine intelligence, the collective intelligence of the community will be facilitated to emerge.

In view of this vision, both research and industry nowadays focus on the creation of CI systems that will realize the above vision.

Successful examples of current systems that attempt to elevate the collective intelligence of their participating users include Wikipedia [27], a free encyclopedia co-edited by web users according to their individual knowledge, problem-solving companies that attempt to find the best idea or solution to a problem through the competition of large numbers of web users and Google [11], the popular search engine that uses the knowledge input of its users to provide accurate findings to their search questions.

As one may observe, CI systems may be substantially different from one another, e.g. in the type of users that they host or in the purpose they have been created for. However, they all seem to share a number of common characteristics. For instance, and depending on the problem that they aim at solving, they all require the participation of an adequate number of users who act individually in various ways, but share, as a community, similar goals.

In this paper we make a first effort to identify the common characteristics shared by CI systems, in order to develop a general framework of their functionality and identify the basic issues related to their optimization.

This modeling is expected to facilitate designers and user communities recognize whether a system has the potential of becoming a CI system, find the direction towards which one should move to maximize the benefit that the community and individual users will receive from this system and decide on the proper technological means, the use of which will elevate the collective intelligence of the community.

The rest of this paper is organized as follows: Section 2 presents the findings of related research literature. Section 3 provides a definition of CI systems, their categorization, as well as the general framework that can describe their functionality. Based on the aforementioned framework, section 4 describes a number of CI systems, identifies some of their problems and proposes certain optimization solutions. Finally, section 5 concludes with the main findings of this paper and provides directions for future work on the field.

## 2. RELATED WORK

A variety of researchers have described the issue of collective intelligence throughout the literature.

First, in a number of studies, CI is either described conceptually or linked with the solution of specific problems that a community may face [9, 12, 15, 22, 26]. Furthermore, and more close to the research objectives of the present work, a few papers in the research literature attempt to model the functionality of CI systems.

Rodriguez [21] proposes a strategy for modeling the collective intelligence of a population by parallelizing it to the individual intelligence and functionality of a human brain. More specifically, and drawing from ideas borrowed from neuroscience, the aforementioned work first describes the way that the human brain finds solutions to problems that it has not yet encountered, by storing the already seen experiences and solutions to lower levels of its cortex, and then by grouping similar events to a more abstract higher-level of the cortex. Thus, when the human brain needs to solve a problem, it uses the higher levels of its cortex to perform a pattern-matching procedure, among the currently encountered problem and the general solutions it has already created to deal with past problems. The paper supports the idea that collective intelligence may be modeled in a similar way, with the solutions offered by individuals lying at the lower level of the hyper-cortex, and the more generic solution patterns being stored at its higher-level. The idea is that community users may then access this generic higher-level of the CI hyper-cortex to find solutions to problems that they encounter. Next, based on this structure, the paper attempts to model the collective intelligence of the scientific community and through this example to propose solutions to certain problems that this community may face.

The functionality of the collective intelligence of a community is also parallelized to that of the human brain in [16]. More specifically, in the conceptual model proposed through the above work, individual participants together with the computational systems that they use, form the neurons of collective intelligence. Then, the community intelligence network is described as a

“supernetwork” that comprises three networks, namely the media, the human and the knowledge network. Community members use the aforementioned supernetwork, to develop their individual cognitive processes and transmit them to other members. This procedure then leads to the collective cognitive processes of the whole community.

Finally, Szuba [23], formalizes collective intelligence using a molecular, quasi-chaotic computational model. In this paper, a method, based on a random PROLOG processor, to measure the IQ of collective intelligence is also proposed.

The aforementioned literature papers present various ways to model collective intelligence. However, these approaches do not focus on the essential problem; that of the CI system design and optimization processes, through which collective intelligence will be able to emerge.

In this paper, CI is viewed and modeled from an engineering point of view. As such, the proposed approach focuses on facilitating designers to identify cases that can be potentially be transformed into effective CI systems, as well as on enabling them to design, implement and optimize CI systems so that the community and individual benefits will be maximized.

## 3. CI SYSTEM FRAMEWORK

### 3.1 CI Categorization

As stated in the introductory section, collective intelligence systems need not to exist only in the World Wide Web. Instead, any situation where large enough groups of people gather, act individually but also share some common community goals could potentially be – with the proper use of technology- transformed into a CI system.

Thus, we may define a collective intelligence system, as a “*system which hosts an adequately large group of people, who act for their individual benefit, but whose group actions aim and may result –through technology facilitation– in a higher-level intelligence and benefit of the community.*”

CI systems may be divided into two categories:

#### 3.1.1 Passive CI systems

In this type of CI systems, individuals act as they would normally do without the system’s presence. Their behavior and actions however, may present specific characteristics that can be used by the CI system to provide each one of them with specific guidelines, hints and coordination so that their shared goal will be more easily achieved. Passive CI systems can be used in almost any case where large groups of people already seem to exhibit collective-mind or swarm-resembling behavior, with each user performing individually but all users sharing a certain number of common goals. This swarming behavior does not constitute collective intelligence per se, as it lacks awareness and intentionality [20]. However, through the use of technology, the crowd behavior can be observed and then modeled into a passive CI system that will provide specific hints to specific individuals so that their community and individual goals will be facilitated.

An example of a passive CI system may be implemented in the field of vehicular network coordination as follows: Take the case of large city roads, where large numbers of vehicles move on daily basis. Drivers perform a simple set of action, e.g. follow the vehicle in front of them, break and accelerate. In addition the

individually act in a variety of ways, for instance some drivers may speed and accelerate suddenly, while others more smoothly, some drivers may prefer leaving a rather long distance between their vehicle and their leading vehicle, while others may leave a shorter distance. Imagine the case when a vehicle is forced to break or significantly slow down its speed. Then a possible scenario is that vehicles following it will break as well, reducing the distances among them and eventually ending up in a traffic congestion, which will not be resolved for quite a while; even after the first vehicle has gained its normal speed. The aforementioned scenario represents a typical swarm-resembling behavior and it can be possibly transformed into a passive CI system. That is, technology can be used –either in the form of fixed spots or in the form of an ad hoc communication among the vehicles– in order to warn, all or specific, following vehicles to slow down so that the first vehicles will have adequate time to move and thus avoid the traffic jam which is about to be created. Through this combination of the behavior of the crowd with technology, the collective capabilities and intelligence of the drivers can be facilitated to emerge.

### 3.1.2 Active CI systems

In this type of CI systems, crowd behavior does not pre-exist but it is created and coordinated through specific system requests. This type of systems can be further divided into the following categories:

- a. Collaborative: Individuals collaborate with one another in order to reach the community and individual targets.
- b. Competitive: In this type of CI, the system triggers user competition, so that the best solution may be reached.
- c. Hybrid: This last type of CI, combines the collaborative and competitive types of systems, through, for instance the competition among groups of collaborating users.

An example of an active CI system of collaborative nature is the popular online encyclopedia, namely Wikipedia. In this type of system, user behavior did not exist prior to system creation, but instead, it was created and triggered through it. In this system, decentralized users collaborate and build on the contributions of each other, in order to create encyclopedic articles. Wikipedia is one of the currently most successful examples of CI systems, since the accuracy of its articles has been found to be similar to that of Encyclopedia Britannica [10].

## 3.2 CI Model

From the above, one may realize that although collective intelligence systems may have different attributes, they all seem to share some common higher-level characteristics.

In this section, an attempt is made to model the most basic characteristics of collective intelligence systems. These attributes include three specific values, namely the set of possible individual user actions, the system state, as well as the community and individual objectives. In addition three important functions necessary for the modeling of the CI system are also described.

### 3.2.1 Set of possible individual actions

The first type of information that is crucial to determine is the set of possible individual user actions ( $\bar{a}$ ). This set includes all actions that an individual user can perform towards the system and may influence the problem at hand.

It should be noted here that the smaller the number of actions each individual user may perform, the simpler the optimal solution of the collective intelligence system is expected to be.

### 3.2.2 System state

The second important aspect that one needs to consider when modeling a CI system, is the system state. The system state  $\bar{s}$  is defined as the minimal set of variables that may fully describe the important aspects of the system.

### 3.2.3 Community and Individual objectives

So far we have modeled the set of actions that users may perform inside the system, influencing its functionality, and the system state. A third important piece of information that needs to be modeled is the community and individual objectives. The community objective ( $\bar{o}_1$ ) refers to the benefit that the community aims at through the use of the CI system, while the individual objectives ( $\bar{o}_2$ ) refer to the benefit that each user foresees in the use of this system.

The aforementioned objectives need to be clearly defined for the specific each time problem. In case the modeled CI system is passive, the community and individual objectives may be extracted through the observation of the population and its actions. In case of an active CI, these objectives can be defined based on the functionality that the designed system needs to perform.

After describing the basic information that needs to be modeled in order to design a CI system, we will next describe the basic functions which are necessary for the effective CI system modeling.

### 3.2.4 Expected user action function

The accurate definition of the function that relates the current actions of the users to an estimation of their expected future actions is highly important, since it will enable the system to better coordinate users and help them reach their collective and individual goals.

Thus, the function of expected user actions ( $\bar{c}$ ) may be defined as follows:

- a. In case that user actions are discrete:

$$\bar{c}_{t+1} = f_1(\bar{s}_t, \bar{a}_t), \quad (1)$$

where  $\bar{s}_t$  is the current system state and  $\bar{a}_t$  are the user actions at time  $t$ .

- b. In case that user actions are constant, , equation 1 becomes:

$$\frac{\Delta \bar{c}}{\Delta t} = f_1(\bar{s}, \frac{\Delta \bar{a}}{\Delta t}), \quad (2)$$

The aforementioned function can be either explicitly defined, using for example behavioral statistics of the targeted population, extracted through social network analysis, or it can be approximated using machine intelligence in the form of e.g. machine learning techniques, and past examples of the behavior of the population.

### 3.2.5 Future system state function.

In order to estimate a future state of the CI system, it will be important to model the function that will estimate the system state a time span of  $\Delta t$ , taking into account the user actions inside this time span and the current system state. This function may be defined as follows:

- c. In case that user actions are discrete:

$$\bar{s}_{t+1} = f_2(\bar{s}_t, \bar{c}_t), \quad (3)$$

where  $\bar{s}_t$  is the current system state at time  $t$  and  $\bar{c}_t$  the expected user actions.

- d. In case that user actions are constant, , equation 3 becomes:

$$\frac{\Delta \bar{s}}{\Delta t} = f_2(\bar{s}, \frac{\Delta \bar{c}}{\Delta t}), \quad (4)$$

where  $\bar{s}$  is the current state of the system and  $\Delta \bar{c}$  are the expected user actions that will take place in the  $\Delta t$  time span.

### 3.2.6 Objective function

The objective function is the function that measures how well the community and individual objectives have been met and it is maximized when these objectives are met in full.

Therefore, the objective function of the community may be defined as follows:

$$O_{1t} = f_3(\bar{o}_1, \bar{s}_t), \quad (5)$$

where  $\bar{o}_1$  are the community objectives and  $\bar{s}_t$  is the current system state.

Similarly, the objective function of individual users may be defined as follows:

$$O_{2t} = f_3(\bar{o}_2, \bar{s}_t), \quad (6)$$

Weighting factors may also be applied on individual and community objectives. Thus, as the system functions, it will aim at maximizing the community and objective functions, taking into account the weights assigned to each one of them.

## 3.3 Issues for further consideration

Through the description of the above values and functions, a high-level collective intelligence system modeling is attempted. However, some further issues need also to be considered:

### 3.3.1 Critical mass

A value that needs to be defined is the critical mass [25] of the CI system, in other words, the minimum number of individuals that need to use the system, so that it will function effectively. Critical mass may differ depending on the community objective of the CI

system, as well as on its type. For instance, in case of a passive CI system, not all users may need to participate, but instead the critical mass may consist of specific key users whose actions will effectively change the collective behavior of the population, bringing it closer to its observed community intentions and objective. In fact, for some types of problems, the number of key users, whose actions can guide an uninformed group has been estimated to be as low as 12.5% of the total population [7, 8].

In case of an active CI system, that starts to function as soon as users participate, the critical mass may be at first roughly estimated for the specific problem e.g. through simulation modeling and then, after an initial period of system use it can be further fine-tuned to match the exact number of necessary users.

### 3.3.2 Task and workload allocation

Based on the type of the CI system that one deals with, the user actions are either pre-defined (passive CI) or defined during the CI design process (active CI). However, whatever the type of the implemented CI may be, a crucial problem that needs to be solved is the actions that each user will be asked to perform at each moment.

In other words, one needs to identify the optimal allocation of tasks that users will be requested to perform so that the community and individual objectives will be, to the best possible extent, maximized.

In the case of passive CI systems, the system should seek to make optimal use of the actions that users already make, so that it will need to engage and change the behavior of only the minimum number of them. In case of active CI, the system should aim at an optimized coordination of user actions so that their individual workload will be to the best possible extent minimized.

Of course, a perfect workload allocation may not always be the target, especially in cases where this would decrease the community objective to a great extent. Instead, what should be sought by the CI during its coordination task, is the best possible balance between the community and individual objectives.

### 3.3.3 Motivation

A final crucial issue that any CI system should address is the issue of user motivation. That is, no matter how well designed a CI system may be, if it is not eventually used by the community that it is targeted at, then it will not be able to increase their collective capabilities. In fact, a recent study [17] on collective intelligence systems reveals that the incorrect identification of the proper user motivating factors is one of the most important launch failure causes of a new CI system.

Thus, upon designing a collective intelligence system, it is important to create the appropriate incentive-based mechanisms that will motivate users to participate. The incentives promoted to users may be extrinsic such as monetary compensation [3], or intrinsic such as the self-fulfillment motivator [17] and social recognition incentives [24].

However, it should be noted here that although the financial incentive is expected to produce more prompt results, however, the incentives of intrinsic motivation seem to be more self-sustained [19].

## 4. MODEL APPLICATION ON CI SYSTEMS

In this section and based on the framework established above, three different types of current collective intelligence systems are analyzed, some of their problems are identified and potential solutions are proposed. The modeling of the CI systems described in this section is presented as an overview in table 1 at the end of the section.

### 4.1 Active CI system modeling

First, two active CI systems are described. These include the collaborative-based system of Wikipedia and the competitive based systems of problem-solving companies.

#### 4.1.1 Collaborative

Wikipedia is probably one of the most famous and influencing collaborative collective intelligence systems. Through this system, users collaborate with one another on the task of encyclopedic article writing. Articles are created spontaneously and then interested users act individually by contributing their knowledge to the created articles.

The state of the system, at each time, can be thus measured by the quality of the articles that it consists of. The community objective is to produce articles of high quality and reliability.

What is mostly interesting about the CI system of Wikipedia is the individual objective of the users. That is, in this system users are not rewarded based on e.g. financial rewards but instead their individual objectives lie on the self-fulfillment that they receive from their contributions.

However, despite its success Wikipedia does not completely lack problems. These include vandalism issues, stemming from users whose individual objectives differ substantially from the typically observed ones. An additional issue faced by Wikipedia is the issue of participation inequality, meaning that the ratio of actively contributing users to “lurkers” is very low. Indeed an approximate ratio of only 1% of the total users that each day use Wikipedia actually contributes to its articles, while the majority makes use of them without any further contributions [4, 18]. This may be explained by the fact that not all users may have the time or expertise to contribute to an article.

A potential solution towards both increasing user participation and preventing vandalism, is to further promote team spirit among users, e.g. by enabling them to create their own communities of practice inside Wikipedia [5]. This solution has been found to increase one’s commitment to the welfare of the community, while it is also expected to prevent “free riding” [2, 19]. In addition, another potential solution that could further increase the capabilities of this CI system is to use the wisdom of inactive users, without assigning them with excessive workload. This could be achieved e.g. by requesting them to rate the articles that they read. This simple action is not expected to burden users that do not wish to actively contribute, but it is expected to make a great deal of difference in estimating the article quality [10] and in identifying exactly which articles need improvement.

#### 4.1.2 Competitive

As described in section 3, apart from collaborative, active CI systems may also be competitive. An indicative example is the recently developed problem-solving companies, which serve as

facilitators between worldwide distributed problem-setters, who act as buyers, and potential problem-solvers, who act as sellers. More specifically, this newly created type of companies seeks to find the optimal solution to the problems set by each of their customers through the competition of web users. Winning solutions, chosen by the customer, are then rewarded on a pre-agreed financial basis. For instance, Innocentive [13], uses the contributions of large numbers of users to retrieve the best solution to R&D and industrial problems, BootB [1] seeks to find the best marketing ideas and DesignBay [6] lies on the competition among web users to find the best graphic design for its customers. The set of possible user actions in these examples is the contribution of their ideas and solutions. In exchange of their contributed ideas and solutions, the individual objective that users seek is the advertised financial reward. The system state in the aforementioned examples is the solutions that have been at each moment received and the community objective is to find the best possible solution.

A potential cause of problems in this type of system is the critical mass. That is, if an adequate number of users do not participate, then the solutions obtained will not meet the criteria of the customers and the system will eventually cease to be used. Thus, it is necessary to find effective ways to continuously balance the financial reward provided, to the time and other requirements of the customers, in order to promptly attract the necessary numbers of contributing users.

### 4.2 Passive CI system modeling

Apart from the active CI systems, which create and trigger user actions, passive CI systems may also be found. In fact, any situation that involves a human crowd, where users may act individually but they all share some common goals –thus acting in a swarm-resembling manner, can be potentially transformed into a passive CI system. The role of the system in this case will be to coordinate specific key users so that the community and individual objectives will be achieved more easily than they would be achieved without system usage.

As mentioned above, an example of such a situation may be observed in the field of vehicular network coordination. In this situation, where large numbers of vehicles seek to reach their destination, drivers perform what they individually believe that will maximize their benefit. The individual objective in this case may include the prompt reaching of one’s destination, the low gas consumption and the individual safety maintenance. The community objective on the other hand is the maximization of the safety of all the network vehicles, as well as the minimization of the traffic congestion. However, since drivers cannot have an overview of the total traffic conditions, they may act in ways different than those that could maximize the community and individual objectives. For instance, through sudden accelerations and break applications they may decrease the distances among them, causing more traffic or even vehicle collisions. A collective intelligence system may be applied in this case in order to maximize the individual and community benefits. This system could for instance view the vehicular network as an ad hoc network, where each vehicle receives information from nearby vehicles. The ambient knowledge that is then created can inform vehicles regarding the conditions that they are about to meet and advice drivers to make changes in their speed or direction so that traffic or collisions will be avoided. For instance, the CI system

installed in a vehicle may receive information regarding decreasing distances among leading vehicles and thus understand that congestion has occurred. In this way, it informs the driver that the current speed of the vehicle should be decreased, so that enough time will be given to the vehicles in front to resolve the congestion. This speed decrease may even be unnoticeable if the congestion information is provided promptly, while it is also expected to affect following cars, causing them to slightly reduce their speed in turn, and thus avoid the congestion.

In addition, the aforementioned CI system needs not to be installed on or coordinate every vehicle on the road, but it only needs to be present in specific key vehicles, the actions of which are estimated to highly affect the traffic. In that way the collective intelligence of the drivers is elevated and used to achieve their individual goals as well as the goals of the whole community.

Potential problems that need to be solved in this type of CI include the definition of the function that estimates future user actions. More specifically, the problem lies in the fact that vehicles constantly enter and leave the network. Thus, the time that a vehicle remains inside the network may not be adequate for an algorithm to estimate its future actions. To resolve this issue past vehicle mobility data patterns could be used to approximate the behavior of vehicles in the current situation.

**Table 1. Modeling of different types of CI systems**

<b>CI system</b>	Wikipedia	Competitive problem-solving companies	Vehicular network coordination system
<b>Type</b>	Active, collaborative	Active, competitive	passive
<b>Set of user actions</b>	Contribute knowledge	Contribute ideas	Accelerate, break
<b>System state</b>	Article quality level	Solutions received	vehicle distances
<b>Community Objective</b>	High article quality	Best possible solution	Minimize traffic congestion, Maximize vehicle safety of the network
<b>Individual objective</b>	Self-fulfillment	Monetary compensation	Prompt reaching of one's destination, low gas consumption, maximize safety of individual vehicle

## 5. CONCLUSION

Collective intelligence is an emerging research field, which seeks to combine human and machine intelligence so that human communities will be able to reach unprecedented results and solutions. As such, this scientific field is expected to greatly engage future research. Collective intelligence systems, i.e. systems that aim at realizing the above CI vision, have recently

started to emerge. The benefits that these systems seem to earn human communities, as well as the fact that, although different in functionality, they all seem to share some basic common functionality and attributes, provide the potential for the design of a general methodology that will allow the systematic development and optimization of CI systems. In this work, an attempt is made to establish a general CI system framework and identify some basic common problems that may impede their success. Then, based on this framework, a number of CI systems are described, their problems are identified and potential solutions are proposed. Future work will include fine-tuning the above methodology, as well as using the developed framework to examine the optimization prospect of various CI systems.

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