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Projecting real world into CrowdIntell network: a methodology

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Abstract

Purpose – The purpose of this paper is to build cyber-physical-psychological ternary fusion crowd intelligence network and realize comprehensive, real, correct and synchronous projection in cyber–physical–psychological ternary fusion system. Since the network of crowd intelligence is the future interconnected network system that takes on the features of large scale, openness and self-organization. The Digital-selfs in the network of crowd intelligence interact and cooperate with each other to finish transactions and achieve co-evolution eventually.

Design/methodology/approach – To realize comprehensive, real, correct and synchronous projection between cyber–physical–psychological ternary fusion system, the authors propose the rules and methods of projection from real world to the CrowdIntell Network. They build the mental model of the Digital-self including structure model and behavior model in four aspects: identity, provision, demand and connection, thus forming a theoretical mental model framework of Digital-self.

Findings – The mental model is excepted to lay a foundation for the theory of modeling and simulation in the research of crowd science and engineering.

Originality/value – This paper is the first one to propose the mental model framework and projection rules and methods of Digital-selfs in network of crowd intelligence, which lays a solid foundation for the theory of modeling, simulation, intelligent transactions, evolution and stability of CrowdIntell Network system, thus promoting the development of crowd science and engineering.

Keywords Projection, Cyber–physical–psychological ternary fusion, Mental model framework, Minds of digital-self, Network of crowd intelligence

Paper type Research paper

1. Introduction

The phenomenon of intelligence is widespread both in the nature (Dorigo and Birattari, 2011; Kennedy, 2011) and in human society (Bernstein *et al.*, 2011; Lévy and Bononno, 1997;

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Bonabeau, 2009). In the current society, there are many cases in which the wisdom of individuals is gathered to achieve better results. For example, there are the business management processes and the coordinated operation of the industrial chains in the economic field; various seminars, various social organizations and their group behavior processes in the social field; national elections and public discussion on social issues in the field of government governance. How to use various intelligence reasonably has always been a complex problem that human beings constantly explore and want to solve.

As human beings enter the internet age, the phenomenon of intelligence is more extensive and complex. As mentioned in Chai *et al.*'s (2017) study, the individuals, enterprises, governmental agencies, smart equipment and articles in the physical space are becoming more and more intelligent in future Web-based industrial operation systems and social operation management patterns. The depth, breadth and patterns of connections between these intelligent entities are constantly expanding, which leads to a large number of crowd intelligent network systems such as e-commerce platform, Wikipedia, network general elections, etc.

Compared to the traditional wisdom phenomenon such as crowd intelligence (Bernstein *et al.*, 2011; Li *et al.*, 2017), collective intelligence (Lévy and Bononno, 1997; Bonabeau, 2009; Malone, 2015), crowdsourcing (Howe, 2006; Buecheler *et al.*, 2010) and citizen science (Irwin, 2002; Riesch and Potter, 2014), the intelligent phenomenon in the network environment is not only large-scale, but also deeply interconnected, widely interconnected and diversified in pattern, and existing in heterogeneous intelligent entities, thus gradually presenting a networked and intelligent economic and social form of Internet of Everything (IoE).

With the further development of society, human beings will enter the era of collective intelligence network (Chai *et al.*, 2017). Big data and artificial intelligence constantly enhance the intelligence of individuals, enterprises, governmental agencies and smart articles. In the meantime, the internet, the Internet of Things (IoT) and cloud computing continue to enhance the depth, breadth and pattern of connections between individuals, institutions (such as enterprises and governments) and smart articles (such as intelligent robots). Under these circumstances, these four intelligent subjects in the physical space and their consciousness (except smart articles, note that the smart articles mentioned in our paper have no consciousness or minds.) in the psychological space are uniformly projected into the network of crowd intelligence, namely, Digital-selfs of individuals, enterprises, governmental agencies and smart articles.

To better describe interaction and cooperation of the intelligent subjects under the environment of crowd intelligence, we build the cyber–physical–psychological ternary fusion system - crowd intelligence network (The crowd intelligence network mentioned in the next part of the paper is abbreviated to CrowdIntell Network and we define the concept of CrowdIntell Network). Physical space and psychological space are from real world, and there are various intelligent entities (such as individuals and enterprises) in physical space and their consciousness in psychological space. Cyber space offers more possibilities of connections of different Intelligent subjects in physical space and expands depth, breadth and patterns of connections. Therefore, the cyber space, physical space and psychological space are ternary fusion and the unity of opposites in CrowdIntell Network system. The Digital-selfs in cyber space is projected from the intelligent subjects and their consciousness (If they have) in the real world and the Digital-selfs reflect the behavior, consciousness and information of the intelligent subjects in the real world. In order to realize the interaction, cooperation and evolution of various Digital-selfs of individuals, enterprises, governmental agencies and smart articles in the CrowdIntell Network, firstly, we need to achieve projection comprehensively, authentically, correctly and synchronously from the real

Intelligent subjects in physical space and their consciousness in psychological space to the CrowdIntell Network. In other words, we need to build the mental model and interconnected model of various Digital-selfs, thus laying a solid foundation for the theory of modeling, simulation, intelligent transactions, evolution and stability of CrowdIntell Network system, which are the essential questions of Crowd Science and Engineering (CSE) (Chai *et al.*, 2017). Therefore, we build cyber–physical–psychological ternary fusion system and propose the methodology of projection from real world to CrowdIntell Network in this paper.

The contributions of this paper can be summarized as follows:

- We propose the rules and methods of projection from real world to CrowdIntell Network to realize comprehensive, real, correct and synchronous projection in cyber–physical–psychological ternary fusion space.
- We establish a general model framework in terms of structure model and behavior model from four aspects: identity, provision, demands and connections of Digital-self, thus forming a theoretical model framework of Digital-self.
- We propose the mental model to realize a synchronous projection in structure, information, behavior and consciousness between Intelligent subjects and Digital-selfs.

The rest of the paper is organized as follows. In Section 2, we review some related work about traditional crowd intelligence and modeling methods and we introduce some work on cognitive computing and mind computing. In Section 3, we define some related concepts about the CrowdIntell Network, introduce cyber–physical–psychological ternary fusion CrowdIntell Network and highlight the general modeling framework of Digital-self in CrowdIntell Network. In Section 4, we introduce projection rules and methods from physical world to CrowdIntell Network. Section 5 concludes the paper and lists some challenges in the future.

2. Related work

Crowd intelligence is the key point of intelligent science and focus on seeking for optimized solutions to complex problems.The concept of swarm intelligence originated from the observations of Wheeler, an entomologist in the biology field. In the 1980s, researchers from multiple disciplines were inspired by the wisdom of group behavior in the social groups, and proposed swarm intelligence (Swarm AI) (Bonabeau *et al.*, 1999). The ideas and methods of swarm intelligence are often used as the theoretical basis of economic simulation, multi-agent modeling and complex adaptive system modeling (Xuesen *et al.*, 1993). To solve complex problems, scientists have made some achievements in traditional crowd intelligence such as collective intelligence (Lévy and Bononno, 1997; Bonabeau, 2009), crowdsourcing (Howe, 2006; Buecheler *et al.*, 2010; Leal *et al.*, 2017) and citizen science (Irwin, 2002; Riesch and Potter, 2014) aiming at limited scale of homogenous and isomorphic agents. However, CrowdIntell in the field of Crowd Science is different from traditional crowd intelligence. We pay attention to solve the interaction, cooperation and evolution problems about large-scaled heterogeneous and isomerous agents such as individuals, enterprises, institutions and goods that are deeply interconnected in the internet environment. Therefore, it's vital to build the model to achieve projection comprehensively, authentically, correctly and synchronously from the real Intelligent subjects in physical space and their minds in psychological space to the CrowdIntell Network.

The Crowd Science is based on the System Theory, Information Theory, Computer Science, Management, Economics, Sociology, Psychology and other subjects, and becomes a

new interdisciplinary direction (Chai *et al.*, 2017), therefore, we need to make full use of multidisciplinary knowledge to model the cyber–physical–psychological ternary fusion space and realize projection. In the field of complex crowd intelligence system, many scholars have done some jobs such as Agent-based artificial society, semantic link network, Internet of Minds (IoM) and some works on cognitive computing and mind computing.

Agent and Multi-agent System is one of the research directions of distributed artificial intelligence and Agent-based modeling is a powerful simulation modeling technique that models social life as interactions among adaptive agents who influence one another in response to the influence they receive. Agent structures emphasize direct couplings of action to perception, and decentralization of processing, dynamic interaction with the environment, and intrinsic mechanisms to cope with incomplete knowledge (Sosa *et al.*, 1990), and Agent system is autonomous, reactive and socially interactive (Wooldridge and Jennings, 1995). So Agent-based modeling and simulation is an effective way to study complex systems and has been applied to the social field (Srbljinović *et al.*, 2002), economic field and military field (Ilachinski, 2000) to model and simulate complex behaviors between different intelligent groups. Jiang *et al.* (Jiang and Jiang, 2014; Jiang and Jiang, 2015) combined social network research with multi-agent methods to find the correlation between social networks and multi-agent systems, and proposed a model framework about social networks based on multi-agent.

In the interaction process of agents, the consciousness of their ontologies is very important. Many scientists expect to improve crowd intelligence by studying human intelligence and they characterize, simulate and calculate human mental characteristics from the perspective of psychology and cognitive science. Researchers have proposed mental models such as ACT-R (Anderson, 1976), Soar (Laird *et al.*, 1987), LIDA (Franklin *et al.*, 2014), etc. However, due to the limitations of multiple disciplines, there has not been widely used in computer science. In order to introduce cognitive computability into modeling research (Li *et al.*, 2003), presents AASC, an Agent architecture based on BDI (belief–desire–intention) model and situation calculus, which provides the facilities for representing mental states of Agent, such as belief, goal, strategy and so on, reasoning about action and planning, and AASC is served as a uniform platform for interpreting the autonomy of Agent and constructing various types of Agents. Ye *et al.* (2018) proposed a general cognitive architecture that attempts to adapt all the aspects of agent's decision-making in artificial societies based on agent modeling technique.

In the research field of modeling multi-space fusion systems, up to now, there have been studies on fusion space of physical, mental, social and cyber space, etc. Cyber-physical systems (CPS) (Baheti and Gill, 2011) is a new generation of systems with integrated computational and physical capabilities that can interact with humans through many new modalities, and CPS will be used in next-generation space designing vehicles and fully autonomous urban driving. Zhuge (2011) proposed a methodology about semantic linking through spaces for cyber-physical-socio intelligence. Diverse spaces will emerge, evolve, compete and cooperate with each other to extend machine intelligence and human intelligence in the Cyber-Physical-Physiological-Psychological-Socio-Mental Environment (CP^3SME). Wang *et al.* (Fei-Yue and Jun, 2017) proposed the blueprint for IoM, discussing its concept, issues and platforms, which can be used in cyber-physical-social-systems (CPSS).

The above researches take several mental factors such as emotion and short memory into consideration; however, there is lack a of systematic research studies. In the conceptual framework of Psychology, the concepts of Psychology can be divided into two parts: psychological process and mental disposition. Psychological process includes cognition, emotion and volition, in the meantime, mental disposition includes ability, temperament,

personality, values, motives, preferences, intentions, etc. Considering the difference of the two parts, the psychological process is more influenced and motived by the current context, meanwhile, the mental disposition reflects more the individual's past life experience and the special constraints that have been formed (Bernhardt, 1947; Buxbaum, 2016). So in our paper, we apply the above psychological related theories and draw on the agent structure modeling technology, then we build cyber–physical–psychological ternary fusion space and realize projection from individuals, enterprises, governmental agencies and smart articles in the physical space and their consciousness in the psychological space to Digital-selfs in the network of crowd intelligence.

3. Cyber–physical–psychological ternary fusion CrowdIntell network

In the network of crowd intelligence, firstly, we need to clarify a few concepts. What is CrowdIntell? What is Intelligent subject? What is Digital-self? What is CrowdIntell Network? What is intelligence in CrowdIntell Network? In addition, what's consciousness in the environment of crowd intelligence?

Definition 1. The intelligent phenomenon in the network environment is not only large-scale, but also deeply interconnected, widely interconnected and diversified in pattern, and exists in heterogeneous intelligent entities such as individuals, enterprises, governmental agencies and smart articles. The intelligence of heterogeneous intelligent entities can combine to achieve one goal or finish one task. We call this intelligence in the network environment as Crowd Intelligence, which is abbreviated to CrowdIntell.

Definition 2. In CrowdIntell environment, four types of intelligent entities of individuals, enterprises, governmental agencies and smart articles in the physical space are called Intelligent subject.

Definition 3. In the network of Crowd Intelligence, Digital-self in cyber space is the unified mapping of Intelligent subject in physical space and their consciousness in psychological space. Digital-selfs and Intelligent subjects connect, interact, cooperate and game with each other by means of cyber space, and Digital-selfs assist Intelligent subjects to make decisions finally. Digital-self not only describes the static attribute information and behavior information of the Intelligent subject, but also further depicts the consciousness of them, which also reflects the characteristics of the projection of everything in CrowdIntell Network.

The Digital-self is different from Digital Twin in IoT. Digital Twin refers to digital virtualization of actual manufacturing processes and product static status in the IoT, Industry 4.0, and advanced manufacturing. In essence, Digital Twin realizes projection about smart articles from physical space to cyber space, but it has no consciousness.

Definition 4 The Digital-selfs reflect the behavior, consciousness and information of the intelligent subjects in the real world and they constitute the network of crowd intelligence through interconnection, which is called as CrowdIntell Network or Network of CrowdIntell (NCI).

Definition 5. The Intelligence in CrowdIntell Network is the combination of artificial intelligence and human intelligence. The Intelligent subjects have professional skills and comprehensive skills, which reflect the abilities of intelligence of them. At the same time, all Intelligent subjects have psychological process and mental disposition except smart articles and we call these psychological process and mental disposition Consciousness.

The intelligence of Intelligent subjects reflects their abilities and their consciousness may guide their behaviors. In CrowdIntell Network, the intelligent subjects of individuals, enterprises, governmental agencies and smart articles in the physical space all have intelligence and the intelligent subjects of individuals, enterprises and governmental

agencies have consciousness. After projection, the Digital-selfs also have the same intelligence and minds as their own Intelligent subjects and the Digital-selfs in CrowdIntell Network make decisions through complex game processes under the influence of the minds projected from psychological space and recorded by Digital-selfs. Then the decisions and suggestions will be fed back to the Intelligent subjects and help Intelligent subjects make better choices. In this process, the intelligent level of Intelligent subjects will be improved. Note that Digital-selfs of smart articles have intelligence and do not have minds. For example, automated guided vehicle can travel along a defined path and complete the transportation work according to a preset procedure. It has the ability of transportation, but cannot think.

In CrowdIntell Network, cyber space, physical space and psychological space are the space of ternary fusion. The cyber–physical–psychological ternary fusion CrowdIntell Network is a complex space in which Intelligent subjects in the physical space and their consciousness in the psychological space are uniformly projected into cyber space as Digital-selfs. Cyber space offers more possibilities of connections of different Intelligent subjects in physical space and expands the depth, breadth and patterns of connections. Digital-selfs and Intelligent subjects can interact and cooperate by means of cyber space. The characteristics of the CrowdIntell Network can be summarized as follows:

- Intelligent subjects such as individuals, enterprises, governmental agencies and smart articles in the physical space and their consciousness in the psychological space are uniformly projected into CrowdIntell Network as Digital-selfs comprehensively, authentically, correctly and synchronously.
- CrowdIntell Network is polycentric and Digital-selfs realize precise interconnection in a point-to-point way.
- Large-scale online heterogeneous and isomerous Intelligent subjects interact with each other to realize collaboration and evolution of Intelligent subjects in CrowdIntell Network.

In cyber–physical–psychological ternary fusion CrowdIntell Network, cyber space is a space characterized by the use of electronics and the electromagnetic spectrum to store, modify, and exchange data, which provides a medium for information exchange. Physical space and Psychological space are from the real world; meanwhile, Intelligent subjects in physical space and their consciousness in psychological space are projected as Digital-selfs into CrowdIntell Network together.

3.1 Cyber space

Cyber space is a domain characterized by the use of electronics and the electromagnetic spectrum to store, modify, and exchange data via networked systems and associated physical infrastructures (Morgan, 2011). Cyber space is the foundation of structure and interconnection of CrowdIntell Network, meanwhile, it is the carrier of CrowdIntell Network. Cyber space offers more possibilities of connections of different Intelligent subjects in physical space and expands their connections. Only with the help of cyber space can the depth, breadth and patterns of connections of Intelligent subjects expand constantly. On the one hand, the data and information in the CrowdIntell Network need to be stored and exchanged by means of the internet or IoT technologies, which are the basic technologies of cyber space. On the other hand, both Intelligent subjects and Digital-selfs need to interact with each other with the help of the connection of cyber space.

3.2 Physical space

Physical space consists of various Intelligent subjects, such as individuals, enterprises, governmental agencies and smart articles, and all of these Intelligent subjects have intelligence. The intelligence of Intelligent subjects reflects their ability to provide for other Intelligent subjects. At the same time, every Intelligent subjects will have demands including tangible material demands, intangible spiritual demands and other demands to make themselves develop and evolve. In the physical world, Intelligent subjects are not isolated and they need to collaborate with each other, therefore, each of them has many connections such as friend connection, consanguinity connection, business connection and government connection.

So in the physical space, the characteristics of Intelligent subjects can be described from four aspects: (I) identity of Digital-self that describes who the Digital-self is, (II) provision of Digital-self that describes what the Digital-self can provide for the others, (III) demand of Digital-self that describes what the Digital-self will need, (IV) connection of Digital-self that describes the interaction and transaction relationship between different Digital-selfs, that is, **Intelligent subject** = <Identity, Provision, Demand, Connection>. Each of these four components may include more than one items except *Identity*. For example, a person can be described as:

Person = <*Tom*, *programming ability*, *food and water*, *Tom's connections*> where Tom's connections may be friend connection in soccer field C_1 = (*Sam*, *Messi*) and consanguinity connection C_2 = (*Jack*, *Lily*, *John*)

3.3 Psychological space

In the future CrowdIntell economical society of IoE, all decisions and behaviors are influenced by consciousness and minds (The smart articles execute actions according to a preset procedure after perception because they don't have consciousness or minds.). The goal of CrowdIntell Network is to ensure that Intelligent subjects can interact, cooperate with each other and achieve co-evolution under the influence of consciousness in the psychological space and to avoid the negative and destructive events. The consciousness of Intelligent subjects is complex and diverse. Suppose there is a transaction scene of buying milk for a person Tom. In the process of deciding to buy milk, the mental factors that should be considered include preference, working memory, cognition, emotion, etc. Because Tom's preference of taste will influence the choice of sweet milk or yogurt. In addition, his working memory about the milk that he bought three days ago will make him buy the same milk or not. Besides, the choice of product packaging may have something to do with his cognition and his emotions at that moment will influence whether he buys or not. Not only individuals but also enterprises and governments have minds and consciousness such as openness of enterprise, innovation of enterprise and social responsibility, etc. All of these traits will influence the interaction, cooperation and evolution between different Digital-selfs. Therefore, the consciousness of Intelligent subjects in the psychological space is vital and essential in the process of decision-making and psychological space is one of the important aspects of cyber–physical–psychological Ternary Fusion CrowdIntell Network. We should make sure that the consciousness of Intelligent subjects can be projected into CrowdIntell Network comprehensively, authentically, correctly and synchronously.

3.4 Model of digital-self in cyber–physical–psychological ternary fusion space

The Intelligent subjects in physical space and the consciousness of them in psychological space are projected as Digital-selfs in CrowdIntell Network, thus forming cyber–physical–psychological ternary fusion space. Based on general agent structure and psychological

related theories, we build the mental model of the Digital-self, which includes structure model and behavior model.

3.4.1 Structure model of digital-self. The structure model of Digital-self reflects the structure and the minds recorded by Digital-selfs of CrowdIntell Network and it is the projection from real world to CrowdIntell Network in the aspect of Intelligent subjects and their consciousness. The structure model consists of seven components: Attribute Set of Digital-self, Knowledge Library of Digital-self, Strategy Library of Digital-self, Mental Module, Perception Module, Decision-making Module and Action Module. Figure 1 presents the basic structure model of Digital-self from four aspects: identity, provision, demand and connection.

3.4.2 Attribute set of digital-self. Structural information is the initial interactive information before the transaction between Digital-selfs, therefore, the attribute set of Digital-self should represent the basic structural information of the Digital-selfs, that is, the

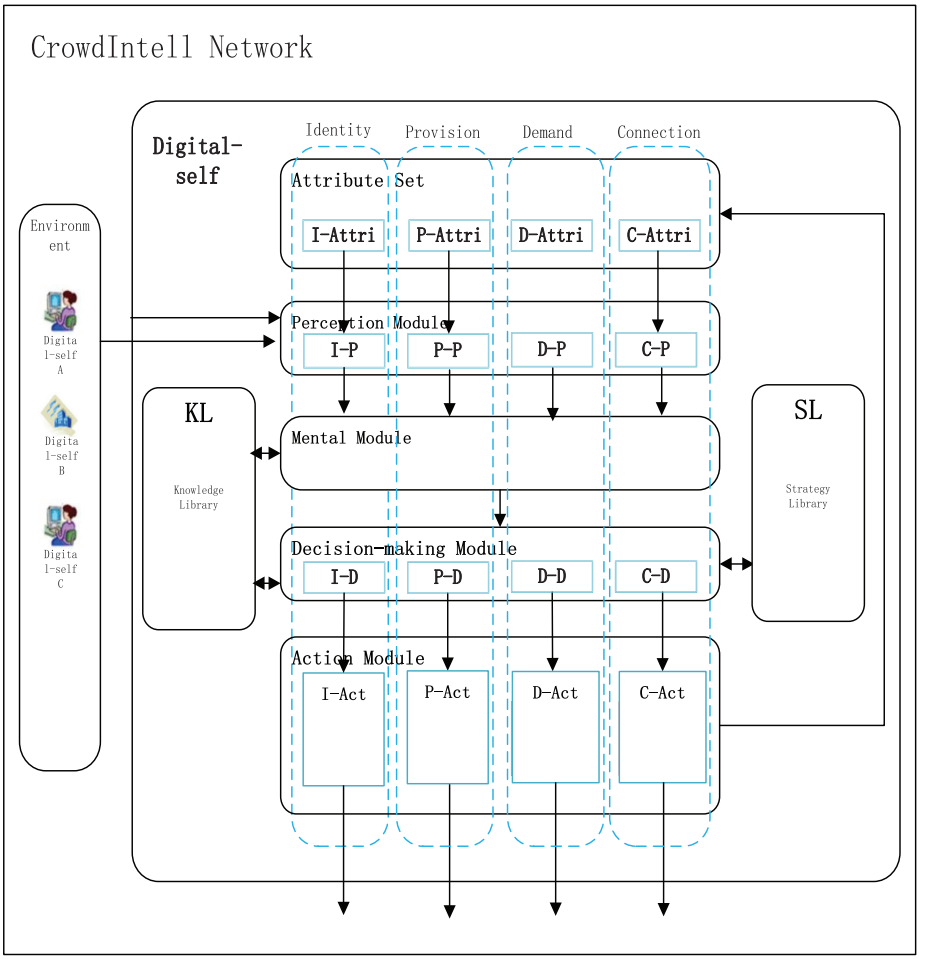

Figure 1. The structure model of Digital-self in CrowdIntell Network consists of seven components, where I- represents the information about identity of the Digital-self, P- represents the information about provision of the Digital-self, D- represents the information about demand of the Digital-self and C- represents the information about connection of the Digital-self. The seven components are Attribute Set of Digital-self, Knowledge Library of Digital-self, Strategy Library of Digital-self, Mental Module, Perception Module, Decision-making Module and Action Module

basic composition parameters of the transaction subjects and objects. In the meantime, it should contain the static function information so that Digital-selfs show what they can do. Hence, after projecting real world into CrowdIntell Network, the structure model contains structure attribute set and function attribute set from the perspective of structure composition, that is, $AS = <SAS, FAS>$, where AS represents Attribute Set of Digital-self, SAS represents structure attribute set and FAS represents function attribute set including professional skills and comprehensive skills. The structure attribute set can be divided into basic structure attribute set *BSAS* and extended structure attribute set *ESAS;* however, not all Digital-selfs contain extended structure attribute set. Hence, we can summarize that $AS = <BSAS, [ESAS], FAS>$, where the attributes in square brackets may be null.

The attribute set of Digital-self can be described as four aspects:

(1) Identity of Digital-self includes BSAS (such as name, ID number, date of birth or manufacture, contact information, etc.), ESAS (such as age, etc.) and FAS that describes what Digital-self can do. For example, for Digital-self of individuals, BSAS also includes information such as height, weight and various parameters of the body; for the Digital-self of enterprises, BSAS usually refers to the enterprise department composition, personnel structure and other information; for the Digital-self of governments, BSAS usually includes information such as institutional department composition, personnel structure and administrative level, etc. ESAS is the extended attribute information provided to understand each other and reach transaction between Digital-selfs, for example, inferring age from data of birth: *date of birth - > age*. FAS shows the static function and ability of Digital-selfs, for example, a person can water the flowers and an enterprise can produce milk;

(2) Provision of Digital-self describes what the digital-self can provide. We can describe the attribute set from the perspective of provision as: $AS = <$*what to provide*, *detailed information about provision*, *provision function* $>$. Where *what to provide* may be goods or knowledge, *information about provision* may be the quantity, quality, time and location of supply and *provision function* may be releasing provision information and counting historical provision records;

(3) Demand of Digital-self describes what the digital-self will need. We can describe the attribute set from the perspective of demand as: $AS = <$*what to demand*, *detailed information about demand*, *demand function* $>$. Where *what to demand* may be goods or skills, *information about demand* may be the quantity, quality, time and location of demand, and *demand function* may be releasing demand information and predicting demand in the future and

(4) Connection of Digital-self describes the interaction and transaction relationship between different Digital-selfs. We can describe the attribute set from the perspective of connection as: $AS = <$*identity in connection*, *detailed information about connection*, *connect function* $>$. Where *identity in connection* may be son, father, boss or employee, *detailed information about connection* may be friend connection in soccer field C_1 = (*Sam*, *Messi*) and consanguinity connection C_2 = (*Jack*, *Lily*, *John*), and *connect function* may be establishing new connections and disconnecting old connections. The connection set of a Digital-self includes friend connection, consanguinity connection, business connection and government connection and each connection may include many subsets.

3.4.3 Knowledge library of digital-self. The knowledge library of Digital-self mainly stores declarative knowledge, which includes autobiographical memory (Brewer, 1986) and other

knowledge such as reasoning rules, constraints and knowledge learned in the process of development and evolution and these knowledge will be used in decision-making process. The autobiographical memory refers to a mixed memory of a Digital-self's complex life events, closely related to the self-experience of memory. The reasoning rules refer to some rules that the Digital-self use in the process of semantic reasoning, spatio-temporal reasoning and logical reasoning. The constraints refer to semantic constraints, numerical constraints, property restrictions, etc. The knowledge includes knowledge about identity, provision, demand and connection:

- The knowledge about identity includes static knowledge, such as stable environment and common sense knowledge (such as national policies, industry standards, etc.) and the information of Digital-self that remains unchanged, and dynamic knowledge such as self-renewing information;
- The knowledge about provision refers to historical provision information set and completed transaction information, including the detailed information of transaction subject and object, transaction records, transaction logistics information, transaction evaluations, etc.;
- The knowledge about demand refers to historical demand information set and completed transaction information, including the detailed information of transaction subject and object, transaction records, transaction logistics information, transaction evaluations, etc. and
- The knowledge about connection contains historical information about my connection in CrowdIntell Network.

3.4.4 Strategy library of digital-self. Digital-selfs in the CrowdIntell Network interact, cooperate with each other and achieve co-evolution by means of game strategies of competition and cooperation. The strategy library mainly stores strategic knowledge, which refers to the Digital-self's understanding of the task in the transaction situation, the choice of strategic methods and the regulation of the transaction process. Meanwhile, the strategy library stores many strategies, including but not limited to perception strategies, self-adjusting strategies, cooperative strategies, competitive strategies, etc. In addition, the strategies learned during the evolution of the Digital-self are also stored in the strategy library. All of these strategies will be used in decision-making process of Digital-selfs.

3.4.5 Mental module. In the process of interaction between Intelligent subjects of physical space, their consciousness of psychological space play an important role. Consciousness can affect the decision-making of the Intelligent subjects, which also reflects the intelligence and complexity of the Intelligent subjects. Therefore, in the process of Digital-self modeling, the consciousness factors must be considered. The contents of consciousness are very complex. At present, there are many theories in cognitive science and brain science research, however, there are few computable model theories, and most of the researches of cognitive science and brain science are aimed at individuals. However, in the CrowdIntell Network, all Digital-selfs can record the minds projected from Intelligent subjects except the Digital-self of smart articles, we need to establish a unified mental model framework. (The main difference between mental model of smart articles and mental model of the other three Digital-selfs is that there is not mental module in the mental model of smart articles.)

The influence of consciousness and mind on decision-making is too complex to be described by linear relations. In mental module, we need to consider the influence of multiple mental factors, and we need to consider that the mental components of different Digital-selfs

of individuals, enterprises and governmental agencies may be different. Hence, We define the general mind framework of Digital-selfs as $M_D = < M_1, M_2, \ldots, M_n >$, where M_n represents the *n-th* component of mind of the Digital-self. Here we list some minds recorded by Digital-self of individuals and enterprises.

For the Digital-self of individuals, the arousal refers to a state of alertness and it indicates whether the Digital-self is mentally and physiologically prepared to respond. Then the other factors in mental module are divided into two parts: psychological process and mental disposition. The psychological process that includes cognition, emotion and volition will influence the decision-making process under the effect of attention. The attention plays an important role in the whole psychological process and it influences decision by focusing on different mental factors in different transaction. The cognition refers to the process in which people acquire knowledge or apply knowledge, or the process of information processing. It is the most basic psychological process of human beings. In our model, cognition mainly includes working memory, which is usually called short-time memory and consists of the processes that involve storing and managing information that is required for accomplishing such key tasks as reasoning, comprehension and general learning. In addition, it can help Digital-selfs make decisions.The emotion is a part of the whole attitude and it is in harmony with the inward feelings and intentions. It is a physiologically complex and stable physiological evaluation and experience of attitude; meanwhile, it can influence the decisions of Digital-selfs. The volition is the psychological process in which people consciously determine their purpose and govern their actions to overcome difficulties to achieve their intended purpose. For example, Digital-selfs can make their decisions under the influence of certain volition such as self-control. The mental disposition, which includes ability, temperament, personality, values, motives, preferences, intentions, etc. may influence the decisions and lead to certain actions and transactions directly. For example, the personality of Digital-self is a trait that can influence behaviors stably in a long time and the preference will make the Digital-self do certain thing or choose certain goods in certain time.

Therefore, for the Digital-self of individuals, the mental module can be described as $M_{DI} = < A, V, E, Md, W, M_{other} >$, where M_{DI} means the minds of Digital-self of individuals, A, V, E, Md, W represent arousal level, volition factor, emotion factor, mental disposition factors (such as personality and preferences), working memory respectively and M_{other} represents other minds. The values of the components of minds may be discrete or continuous values. In addition, the attention mechanism is reflected in the numerical value of the factors of minds. For the Digital-self of enterprises, the mental module may be $M_{DE} = < Social\ responsibility, Creativity, Openness, Values, M_{other} >$, where M_{other} may include the emotions and volition of the enterprise leaders. Figure 2 shows basic mental components of Digital-self of individuals.

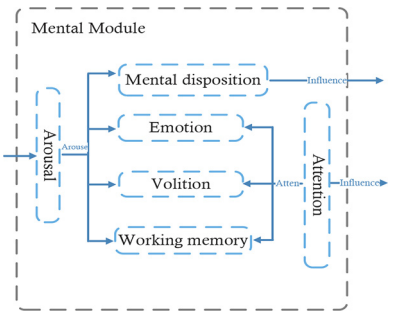

Figure 2.
This is the mental factors of the Digital-self of individual and mental disposition includes ability, temperament, personality, values, motives, preferences, intentions, etc.

3.4.6 Perception module. The perception module needs to perceive two parts: the information of the Digital-self itself and the information of other Digital-selfs in CrowdIntell Network, including identity perception, provision perception, demand perception and connection perception. The perception module needs to perceive the following contents:

- its own identity information and the identity information of other Digital-selfs in CrowdIntell Network;
- its own provision information and the demand information of other Digital-selfs in CrowdIntell Network;
- its own demand information and the provision information of other Digital-selfs in CrowdIntell Networka and
- its own connection information and the connection information of other Digital-selfs in CrowdIntell Network.

3.4.7 Decision-making module. The decision-making module contains identity decision, provision decision, demand decision and connection decision, and each component makes different decisions, which are prerequisites for execution. In the meantime, the decisions will be fed back to the Intelligent subjects to help them make better decisions. The decision-making process will be presented in chapter "Behavior Model".

3.4.8 Action module. The action module is responsible for executing the decisions issued by the decision-making module and providing feedback to the internal environment, such as updating its attribute information, and external environment, such as cooperating with other Digital-selfs, to finish interaction and transaction in CrowdIntell Network. The action process will be also presented in chapter "Behavior Model".

3.4.9 Behavior model of digital-self. The behavior model of Digital-self reflects the behavior of the Digital-self. The structure attributes determine its static function and are the basis of generating behaviors. Therefore, we define the behavior model based on the structure model. Figure 3 shows a behavior model of the Digital-self of individual. (Note that the mental behaviors of Digital-selfs of individuals, enterprises, governmental agencies and smart articles may be different. This challenge needs to be studied in future work.):

- Perception Module can perceive the identity, provision, demand and connection of itself and other digital-selfs from Attribute Set and environment. Then this information will be used to update Knowledge Library and Strategy Library of Digital-self, and be delivered to Mental Module.
- Mental Module receives and checks the information that the Perception Module has perceived. After mind computation, the result will be used to influence the Decision-making Module. (In the Mental Module of Digital-self of individual, the aroused level reflects the state of alertness of the Digital-self. It indicates whether the Digital-self is mentally and physiologically prepared to respond and it arouses mental disposition factors, emotion factor, volition factor, working memory, Knowledge Library and Strategy Library. In the process of mental influence, the mental disposition factors can influence the decision-making process directly and the other mental factors influence indirectly decision-making process under the effect of the attention. Meanwhile, working memory and knowledge in the Knowledge Library and Strategy Library can transform into each other.)

- Decision-making Module is driven by the Perception Module and is influenced by the Mental Module. It is responsible for reasoning and making the decisions. In the process of reasoning and making decisions, Decision-making Module needs to use the knowledge from Knowledge Library and the strategies from Strategy Library. Eventually, Decision-making Module will output the decisions to the Action Module.
- Action Module receives the decisions from Decision-making Module and chooses different components to execute various decisions, thus updating the Attribute Set, Knowledge Library, Strategy Library and Mental Module and finishing interaction with other Digital-selfs eventually. Meanwhile, the actions and decisions will be fed back to the Intelligent subjects.
- In the process of interaction and cooperation among different Digital-selfs, they learn the cooperative game and competition game strategies from the Strategy Library of Digital-self and develop themselves based on the knowledge of Knowledge Library of Digital-self. At the same time, the intelligence of Digital-self will be improved and realize co-evolution eventually.

Here, we take the navigation in intelligent transportation as an example. Each driver is an independent Intelligent subject and his historical behavior data and consciousness and minds will be projected into CrowdIntell Network as the Digital-self of driver. In the process of driving, the Digital-selfs of drivers can perceive the surrounding road conditions (including traffic speed, road congestion, etc.) by means of navigation software. The preferences and will of each Digital-self of drivers may be different and the aspects of their

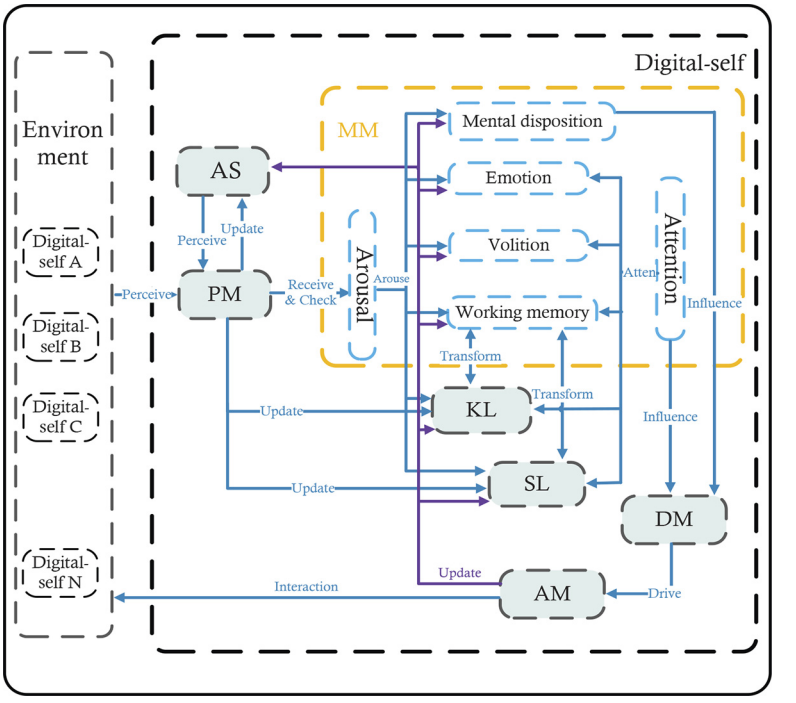

Figure 3.
The Behavior Model of Digital-self of individual. AS, KL, SL represent Attribute Set of Digital-self, Knowledge Library of Digital-self, Strategy Library of Digital-self respectively. MM, PM, DM, AM represent Mental Module, Perception Module, Decision-making Module, Action Module, respectively

attention may be different, which will lead to the decision to choose different routes. For example, a punctual driver may be willing to choose the route that takes the shortest time under current road conditions; however, a driver who pursues safety may choose the flat road instead of the trail. After Digital-selfs make the decision under the influence of minds, each Digital-self of the drivers will re-plan several routes and feed back to the Intelligent subject of the driver, then the driver will choose the better route.

4. Projection from real world to CrowdIntell network

To achieve interaction, cooperation and co-evolution between Digital-selfs in CrowdIntell Network, firstly, we need to realize comprehensive, real, correct and synchronous projection from physical space and psychological space to CrowdIntell Network and build cyber–physical–psychological ternary fusion space. The projection rules and projection methods are vital for the modeling process.

4.1 Projection rules

There are four main projection rules.

4.1.1 Rule 1: bijective projection. The projection from Intelligent subjects of physical space to Digital-selfs of CrowdIntell Network is one-to-one mapping, that is, the projection is a function between the elements of Intelligent subject set and Digital-self set, where each Intelligent subject of physical space is paired with exactly one Digital-self of CrowdIntell Network, and each Digital-self of CrowdIntell Network is paired with exactly one Intelligent subject of physical space. There are no unpaired elements. Therefore, a bijective projection function f: *Intelligent subject* $\rightarrow$ *Digital-self* is an injective and surjective mapping of an Intelligent subject set to a Digital-self set from the mathematical point of view.

4.1.2 Rule 2: data consistency. When projecting the real world into CrowdIntell Network, the data must be consistent between Intelligent subjects and Digital-selfs. At the same time, numerical constraints and data consistency between structure model and behavior model of Digital-self in CrowdIntell Network should be guaranteed. Numerical constraint mainly refers to the range of data. For example, the age of Digital-self of individual cannot be negative. Data consistency means guaranteeing that the value and the unit of measurement are consistent between two models. For example, the demand of a Digital-self of individual is one liter of milk in the structure model; meanwhile, the behavior should be releasing the demand of one liter of milk in the behavior model.

4.1.3 Rule 3: semantic consistency. When projecting the real world into CrowdIntell Network, the Digital-self consists of structure model and behavior model and there are semantic consistency constraints between them. The meaning of the same entity should be same in the structure model and behavior model. For example, a Digital-self of individual needs an apple and the apple means fruit or mobile phone, which should be consistent in the structure model and behavior model of Digital-self.

4.1.4 Rule 4 semantic completeness. The projection from real world to CrowdIntell Network should be semantically complete. All data about Intelligent subject of physical space should be projected to Digital-self of CrowdIntell Network to describe Digital-self and to facilitate the completion of transactions. For example, the basic information of a Digital-self of individual should consist of ID, date of birth, and sex at least. Therefore, In the process of projection, these information should be projected to Digital-self completely.

4.2 Projection methods

In real world, the raw data of Intelligent subjects can be obtained in direct ways, such as the weight and height of an individual, the historical behavior records of an individual and the contact information and addresses of an enterprise. All information about Intelligent subjects should be projected into CrowdIntell Network and recorded by Digital-selfs and these information should be mapped into the components of the structure model in direct or indirect ways. The direct projection means that the basic attribute data such as the weight and height can be projected to Digital-self directly. However, there are some mental data that can't be obtained directly from the raw data of Intelligent subjects. In this case, we can obtain the data from behavior records by means of the methods of mind computation, such as affective computing and sentiment analysis. This way is called indirect projection.

4.2.1 Direct projection. Most of the visible data can be directly mapped to attribute set of Digital-self's structure model. The basic attribute information can be obtained from the internet, various data reports and intelligent equipment, etc. For example, for a Digital-self of individual, the height, weight and lung capacity can be obtained from the physical examination report. The heart rate can be obtained through smart bracelet. The educational information is available on educational websites and his part of friend connection may be available from social network platforms. All of these data will be projected to Digital-self directly.

4.2.2 Indirect projection. Some values, especially the factors related to minds of Digital-self, cannot be retrieved directly from the raw data of internet, various data reports and intelligent equipment. In this case, we can infer or calculate the attribute values of the Digital-self from the original data such as behavior records. Prediction of personality and sentiment analysis based on online behavior data has become a hot spot in the interdisciplinary study of psychology and computer science, for example, predicting personality traits from Facebook Likes data (Kosinski *et al.*, 2013) and based on Weibo (Li *et al.*, 2014) and predicting buying tendency according Weibo and Taobao records (Zhang *et al.*, 2014) and so on. All of these studies demonstrate the computability of the minds and provide a research method to project the minds into CrowdIntell Network.

Otherwise, many components of the mental model may be obtained by means of machine learning and reinforcement learning. For example, the strategies in the Strategy Library from the real world may be rare at the beginning, and we can use machine learning algorithms or some game theoretic models to simulate the interaction between Digital-selfs and generate new strategies and mechanism based on the original strategies projected directly from the real world.

5. Conclusion and future work

In the networked CrowdIntell economical society of IoE, cyber space, physical space and psychological space are ternary fusion and the unity of opposites and interconnection of all things, point to point and polycentric mode are important features of the future economic and social ecology. Therefore, we propose the conception of CrowdIntell Network and build cyber–physical–psychological ternary fusion system. We propose the methodology of realizing comprehensive, real, correct and synchronous projection from real world to CrowdIntell Network.

There are many challenges in the modeling of Digital-self: How to build complete mental module for Digital-self of individuals, enterprises and governmental agencies; how to realize

comprehensive, real, correct and synchronous projection and how to ensure data consistency, semantic consistency and semantic completeness and so on.

References

Anderson, J.R. (1976), "Language, memory, and thought.[J]", *Schenkman Pub Co*.

Baheti, R. and Gill, H. (2011), "Cyber-physical systems[J]", *The Impact of Control Technology*, Vol. 12 No. 1, pp. 161-166.

Bernhardt, K.S. (1947), "Review of psychology, normal and abnormal: an introduction to the study of mind and behavior[J]", *Canadian Journal of Psychology Revue Canadienne De Psychologie*, Vol. 1 No. 3, pp. 152-153.

Bernstein, J., Long, J.S., Veillette, C. and Ahn, J. (2011), "Crowd intelligence for the classification of fractures and beyond", *PloS One*, Vol. 6 No. 11, p. e27620.

Bonabeau, E. (2009), "Decisions 2.0: the power of collective intelligence[J]", *MIT Sloan Management Review*, Vol. 50 No. 2, p. 45.

Bonabeau, E., Dorigo, M. and Theraulaz, G. (1999), *Swarm Intelligence – From Natural to Artificial Systems[M]// Swarm Intelligence: From Natural to Artificial Systems*.

Brewer, W.F. (1986), "What is autobiographical memory?", in Rubin, D.C. (Ed.), *Autobiographical Memory*, Cambridge University Press, New York, NY, pp. 25-49.

Buecheler, T., Sieg, J.H., Füchslin, R.M., *et al.* (2010), "Crowdsourcing, open innovation and collective intelligence in the scientific method: a research agenda and operational framework[C]", *The 12th International Conference on the Synthesis and Simulation of Living Systems*, *MIT Press*, *Odense, Denmark*, 679-686. 19-23 August.

Buxbaum, O. (2016), "Introduction to the study of the mind", *Mental Activity, and Behavior[M]//Key Insights into Basic Mechanisms of Mental Activity*,

Chai, Y., Miao, C., Sun, B., *et al.* (2017), "Crowd science and engineering: concept and research framework[J]", *International Journal of Crowd Science*, Vol. 1 No. 1, pp. 2-8.

Dorigo, M. and Birattari, M. (2011), *Ant Colony Optimization[M]//Encyclopedia of Machine Learning*, Springer, Boston, MA, pp. 36-39.

Fei-Yue, W. and Jun, Z. (2017), "Internet of minds: the concept, issues and platforms[J]", *Acta Automatica Sinica*, Vol. 43 No. 12, pp. 2061-2070.

Franklin, S., Madl, T., D'Mello, S., *et al.* (2014), "LIDA: a systems-level architecture for cognition, emotion, and learning[J]", *IEEE Transactions on Autonomous Mental Development*, Vol. 6 No. 1, pp. 19-41.

Howe, J. (2006), "The rise of crowdsourcing[J]", *Wired Magazine*, Vol. 14 No. 6, pp. 1-4.

Ilachinski, A. (2000), "Irreducible semi-autonomous adaptive combat (ISAAC): an artificial-life approach to land combat[J]", *Military Operations Research*, Vol. 5 No. 3, pp. 29-46.

Irwin, A. (2002), *Citizen Science: A Study of People, Expertise and Sustainable Development[M]*, Routledge, Abingdon.

Jiang, Y. and Jiang, J.C. (2014), "Understanding social networks from a multiagent perspective[J]", *IEEE Transactions on Parallel and Distributed Systems*, Vol. 25 No. 10, pp. 2743-2759.

Jiang, Y. and Jiang, J.C. (2015), "Diffusion in social networks: a multiagent perspective[J]", *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, Vol. 45 No. 2, pp. 198-213.

Kennedy, J. (2011), *Particle Swarm Optimization[M]//Encyclopedia of Machine Learning*, Springer, Boston, MA, pp. 760-766.

Kosinski, M., Stillwell, D. and Graepel, T. (2013), "Private traits and attributes are predictable from digital records of human behavior[J]", *Proceedings of the National Academy of Sciences*, p. 201218772.

Laird, J.E., Newell, A. and Rosenbloom, P.S. (1987), "Soar: an architecture for general intelligence[J]", *Artificial Intelligence*, Vol. 33 No. 1, pp. 1-64.

Leal, F., Malheiro, B., González-Vélez, H., *et al.* (2017), "Trust-based modelling of multi-criteria crowdsourced data[J]", *Data Science and Engineering*, Vol. 2 No. 3, pp. 199-209.

Lévy, P. and Bononno, R. (1997), *Collective Intelligence: Mankind's Emerging World in Cyberspace[M]*, Perseus books, New York, NY,

Li, B., Lu, J. and Zhu, W. (2003), "An agent architecture based on situation calculus[J]", *Journal of Software*, Vol. 14 No. 4, pp. 733-742.

Li, L., Li, A., Hao, B., *et al.* (2014), "Predicting active users' personality based on micro-blogging behaviors[J]", *PloS One*, Vol. 9 No. 1, p. e84997.

Li, W., Wu, W., Wang, H., *et al.* (2017), "Crowd intelligence in AI 2.0 era[J]", *Frontiers of Information Technology and Electronic Engineering*, Vol. 18 No. 1, pp. 15-43.

Malone, T.W. and Bernstein, M.S. (Eds) (2015), *Handbook of Collective Intelligence*, MIT Press, Cambridge.

Morgan, D.R. (2011), *Defending the New Domain: Cyberspace[J]*, Defending the New Domain Cyberspace.

Riesch, H. and Potter, C. (2014), "Citizen science as seen by scientists: methodological, epistemological and ethical dimensions[J]", *Public Understanding of Science (Bristol, England)*, Vol. 23 No. 1, pp. 107-120.

Sosa, R., Xu, Q. and Mohan, R.E. (1990), *Designing Autonomous Agents[M]*, North-Holland Publishing Co.

Srbljinović, A., Penzar, D., Rodik, P., *et al.* (2002), "Agent-based modeling of ethnic mobilization: the former yugoslavia case[C]", *The 1st Lake Arrowhead Conference on Computational Social Science and Social Complexity: Agent-Based Modeling in Social Sciences*.

Wooldridge, M. and Jennings, N.R. (1995), "Intelligent agents: theory and practice[J]", *The Knowledge Engineering Review*, Vol. 10 No. 2, pp. 115-152.

Xuesen, Q., Jingyuan, Y. and Ruwei, D. (1993), "A new discipline of science the study of open complex giant system and its methodology[J]", *Journal of Systems Engineering and Electronics*, Vol. 4 No. 2, pp. 2-12.

Ye, P., Wang, S. and Wang, F.Y. (2018), "A general cognitive architecture for agent-based modeling in artificial societies[J]", *IEEE Transactions on Computational Social Systems*, Vol. 5 No. 1, pp. 176-185.

Zhang, F., Yuan, N.J., Lian, D., *et al.* (2014), "Mining novelty-seeking trait across heterogeneous domains[C]", *Proceedings of the 23rd International Conference on World Wide Web, ACM*, pp. 373-384.

Zhuge, H. (2011), "Semantic linking through spaces for cyber-physical-socio intelligence: a methodology[J]", *Artificial Intelligence*, Vol. 175 Nos 5/6, pp. 988-1019.

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