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Multi-agent systems in construction: a ten-year review

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Abstract

This study critically reviews multi-agent systems (MAS) in construction. Given their autonomous, cooperative, and learning attributes, MAS are a promising approach to address the essential problems of “collaboration and consensus” among stakeholders in construction projects. Despite the development of many agent-based technologies and applications in recent years, relatively few reviews have been reported on this area. Based on selected papers, this study proposes a novel framework of MAS in construction. It focuses on collaboration and consensus in construction projects, and comprehensively organizes three dimensions of MAS, namely “application–issue–attribute”. Based on this framework, the applications and issues in construction domain can be facilitated with appropriate attributes of MAS, and it can also help find the potential applications of MAS in construction. Furthermore, this study clarifies the advantages of MAS and support collaboration and consensus in construction domain. Finally, the development of MAS in construction is presented, and future research directions are recommended.

Keywords: Multi-agent system; Agent; Construction; Collaboration; Consensus

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Introduction

Multi-agent systems (MAS) have developed rapidly in recent years because of their strong capability in solving complex and dynamic problems. MAS include numerous intelligent agents that can represent real-world parties without global control and unified objective (e.g. stakeholders in construction projects) (Ren and Anumba, 2004). Given that an individual agent lacks sufficient resources, information, and capabilities, each agent should interact with other agents and environments to maximize its own utility. A complex problem, which involves a distributed environment and several heterogeneous stakeholders, can be bottom-up analyzed by assigning sub-problems to related intelligent agents. Given their autonomy, cooperation, and learning characteristics (Nwana, 1996), intelligent agents can dynamically adjust to a realize system stability and optimization through convergence mechanism (Phanden et al., 2011). Therefore, MAS are considered a promising method for complex systems, because of their dynamic, robust, and parallel working capabilities.

Numerous construction projects are complex systems with distributed heterogeneous stakeholders operating in a dynamic environment. Particularly, fragmentation is considered a serious problem (Ren and Anumba, 2004), that can be significantly solved through collaboration (Xue et al., 2012). However, geographically distributed teams, different backgrounds of participants, dynamic environment, and conflicting interests negatively affect collaboration and consensus. MAS include different agents that can simulate collaboration among different stakeholders with varied interests. Modeling and simulation with MAS can help address and analyze these issues. Therefore, MAS provide an appropriate mean to address the issues of fragmentation and improve collaboration in the construction industry. Previous studies have applied MAS in several issues, including occupant behavior simulation (Azar and Menassa, 2012), project organization (Du and El-Gafy, 2012), collaborative design (Chu et al., 2009; Ren et al., 2011a), dynamic scheduling (Christodoulou, 2009), dispute resolution (El-Adaway and Kandil, 2010), negotiation (Kim and Paulson, 2003; Xue and Ren, 2009), knowledge Systems (Obonyo, 2013) and site management (Kim and Kim, 2010a). Although they seems like various independent issues, in fact, most of these key issues are related to the same question: how to improve “collaboration and consensus” in construction management.

Previous studies obtained remarkable achievements in MAS, however, most of them mainly focused on tackling a specific issue in construction domain. Few studies, if not none, focused on building a comprehensive framework to systematically conclude the applications, key issues and the correlations with agent attributes. Ren and Anumba (2004) did a comprehensive review of MAS in construction, but it still mainly emphasized on specific issues and technology. In other domains, for example in manufacturing, the framework of MAS knowledge has been built several years ago (Shen et al., 2006a).

To bridge this gap, this study proposes an “application–issue–attribute” framework, which summarizes, categorizes and links the applications, the key issues and attributes of MAS in construction. A main difficulty of MAS development is how to appropriately use their attributes to maximize their advantages. This framework relates key issues of MAS with attributes of agents, and then links various applications to the key issues. Based on this framework, the applications in construction domain can be facilitated with appropriate attributes of MAS. On the other hand, the results can also help find the potential applications of MAS in construction.

In addition, different from previous studies, this review is problem oriented rather than technology or application oriented. Namely, MAS are reviewed from the particular perspective of “collaboration and consensus”. The majority of the previous studies and reviews focused on specific issues, applications and technology. But the original and essential problem of “collaboration and consensus” was overlooked. Therefore, this study does not aim to specific applications and issues, but focuses on the key issues related to collaboration and consensus. The results can help further clarify the advantages of MAS in this problem and support collaboration and consensus in construction domain.

Finally, an updated review focusing on the state of art of MAS in construction is provided. Over the last decade, MAS have developed rapidly not only in algorithms and technologies, but in various application innovations as well. An update on MAS in construction is essential. In conclusion, the main aim of this study is to propose a novel framework of MAS in construction. It focuses on collaboration and consensus in construction projects, and comprehensively organizes three dimensions of MAS, namely “application–issue–attribute”. The objectives of this study are outlined as following.

(1) To review and analyze MAS from the particular perspective of collaboration and consensus in construction.

(2) To build an “application–issue–attribute” framework. It will classify the key issues and applications of MAS in construction and correlate them with the attributes of agents. The main application areas of MAS in construction are intended to be identified based on this classification.

(3) To investigate the advantages and disadvantages of MAS in construction and provide the prospects for MAS development.

Methodology

The process of literature review includes four steps, which are shown in Figure 1:

(1) Essential problem identification: This review identifies the essential issue in construction as “collaboration and consensus”. By abstracting and modeling this problem, MAS are considered to be an appropriate method to solve it;

(2) Key issues of MAS observation: General MAS theories are reviewed to find general improvement of MAS, and the state of art of MAS in construction (e.g. methods, algorithms,

techniques and applications) is investigated to find the particular issues in construction domain;

(3) Existing and potential application areas analysis: Existing application areas are identified by reviewing state of the art in construction, and state-of-art applications in other domains (e.g. transportation, manufacturing and information science) offer some potential and future application areas;

(4) Gaps and prospects exploration: Some gaps are found between requirements in construction and the state of art of MAS. Trends and prospects are suggested to narrow the gaps and to improve collaboration and consensus.

Since this paper focuses on MAS in construction domain, the search terms are set as ("multi agent" OR "agent based") AND ("construction" OR "infrastructure" OR "civil engin*") in the searching criterion Topic in the Science Citation Index (SCI) database, and the result was refined to computer science interdisciplinary applications, engineering civil, operations research management science, construction building technology, engineering, and automation control systems domains. After reading abstracts of these papers, some irrelevant papers were excluded. In the end, 98 papers were selected to review. The development of journal papers related to MAS in construction is illustrated in Figure 2, which shows that the number of published papers dropped from 2007 to 2008, but rapidly increased over the last years.

Overview of MAS

MAS have been used for decades, but what the term “agent” refers to is not well defined (Panait and Luke, 2005). Durfee et al. (1987) defined MAS as a loosely coupled network of agents working together to solve problems that individual agents cannot solve on their own. Wooldridge and Jennings (1995) described “agent” as “a self-contained program capable of controlling its own decision-making and acting based on its perception of its environment, in pursuit of one or more objectives”. Other definitions have been suggested. Panait and Luke (2005) considered agent as “a computational mechanism that exhibits a high degree of autonomy, performing actions in its environment based on information (sensors, feedback) received from the environment”. Shen et al. (2006a) opined that an agent is a computer system that can act autonomously to reach its objectives.

The definitions of agent and MAS may vary, but they share common characteristics. Wooldridge and Jennings (1995) identified these characteristics as autonomy, social ability, reactivity, and pro-activeness. This definition was refined by Nwana (1996) to include the following widely-cited behavioral attributes of MAS:

1) Autonomy. This attributes indicates that agents act by themselves rather than being controlled by humans, other agents or entities.

2) Cooperation. This attributes indicates that with cooperation, agents can achieve what they cannot achieve on their own; MAS exhibit a satisfactory performance when agents collaborate well.

3) Learning. This is the key attribute of an intelligent agent, allowing it to evolve over time, adapt to the environment and enhance performance.

Key issues of MAS related to collaboration and consensus in construction

Identification of key issues

MAS provide many advantages, but they remain at the early stage of development with numerous issues that need to be addressed and solved. Bond and Gasser (1988) first cited a list of changes faced by MAS. This list was expanded by Sycara (1998) and improved by other researchers. Previous studies suggested that reaching a stable state of coherent collective behavior in MAS is a major challenge (Christodoulou, 2009). This challenge is referred to a “consensus” problem, implying the need “to reach an agreement regarding a certain quantity of interest that depends on the state of all agents” (Olfati-Saber et al., 2007).

In most MAS, groups of agents should reach consensus over various interests and make common decisions to solve a number of problems (Olfati-Saber and Murray, 2004). However, agents are autonomous and lack global perspective, control, or sufficient data to reach a consensus automatically. Thus relevant algorithms or mechanisms have to be designed to facilitate the process.

Based on a previous work (Sycara, 1998), the main issues derived from the consensus problem in MAS can be classified into seven aspects: (1) individual agent reasoning, (2) planning and scheduling, (3) organization, (4) resolving conflicts and negotiation, (5) resource and task assignment, (6) communication management, and (7) adaptation and learning. These dimensional problems can further be categorized into three agent behavioral attributes, as shown in Figure 3. The research questions pertinent to each issue are illustrated in Table 1.

Autonomy and individual agent reasoning issues

The reasoning of individual agent reasoning is important to MAS coherence because agents can rationalize the behavior of others and even avoid potential conflicts. Many studies on MAS have formalized a logical architecture for the sophisticated reasoning of agents. In particular, these studies tended to focus on specific aspects of agent reasoning, (e.g. diagnostics and error recovery) that are considered important in MAS. Odrey and Mejia (2003) developed a multi-level, multi-layer hierarchy to recognize and recover error. This hierarchy included a production module and an error recovery module, as well as a mediator module connecting the first two. Based on this architecture, agents exhibited responsive and adaptive capabilities for self-adjustment.

Rojas and Mukherjee (2006) proposed a general-purpose situational simulation framework in construction domain. This framework implies that the reasoning processes can be isolated using a conceptual classification of problems in construction. This agent reasoning, which is referred to as “general purpose multi-agent framework”, consists of several basic *modules*, used to exchange information and act with a specific operator. The simulation platform based on this framework can reflect realistic situations and improve the construction process.

Cooperation issues

Planning and schedule

MAS are an effective means to realize planning and scheduling (Phanden et al., 2011). In particular, this tool can be used by agents to improve coherence by planning their actions (Sycara, 1998). The scheduling problem widely existing in construction is typically considered a non-deterministic polynomial (NP) problem (Pinedo, 2012). This kind of problem has polynomial computation complexity, and its time consumption increases exponentially with problem size. Compared with traditional approaches, agent-based approaches have significant advantages for this problem: parallel computation with high efficiency, dynamic adaptation, and robustness with fault tolerance (Shen et al., 2006b).

MAS can improve scheduling efficiency because each agent can operate concurrently. To implement this parallel operation, ant colony algorithm is widely used in agent-based scheduling (Mullen et al., 2009; Shyu et al., 2006). MAS can also be used with several traditional scheduling techniques to improve efficiency. One attempt is to improve Petri net efficiency with MAS (Molinero and Nunez, 2011; Stuit and Szirbik, 2009). MAS can likewise be combined with modern information technologies, such as the Internet, distributed computations, and cloud framework (Singh and Malhotra, 2012).

Dynamic adaptation is another advantage of agent-based scheduling. Most construction projects operate in a dynamic environment, because tasks, designs and resources may change and other unpredictable events often occur during project execution. In addition, predicting the exact time of each task is difficult. A dynamic and robust schedule should be created to avoid crashing cost, time, human resources, or facilities, especially in the construction industry (Hall, 2012). Ouelhadj and Petrovic (2009) compared several algorithms of dynamic scheduling, including heuristics, meta-heuristics, MAS, and other artificial intelligence algorithms. The comparative study demonstrated that MAS show potential in current and future research in dynamic scheduling (Ouelhadj and Petrovic, 2009).

Apart from the traditional algorithms used in MAS (e.g. genetic algorithm, ant colony algorithm and particle swarm optimization), several novel algorithms have recently been developed to integrate with MAS (Kim and Paulson, 2003; Taghaddos et al., 2012). Kim and Paulson (2003) developed an economics-inspired approach, which adopted a common conception known as “compensatory” used in welfare economics. Taghaddos et al. (2012) constructed a model inspired by “persistence of vision”. This model disintegrated a scheduling problem into resource allocation problems at each point of time and then solved each resource allocation problem using the auction method.

Organizations

Organizations are generally considered a structure of information and control relations existing among agents, providing a high level view of cooperative problem solving (Sycara, 1998). Horling and Lesser (2004) identified 10 types of organizational structure of MAS: (1) hierarchy, (2) holarchy, (3) coalition, (4) marketplace, (5) congregation, (6) society, (7) federation, (8) matrix, (9) team, and (10) compound organization. Each organizational structure has advantages and disadvantages, thus no organization is definitely better than the others.

Other studies have considered the organization of MAS for specific applications. Son and Rojas (2011) introduced an organizational framework for temporal team collaboration in large-scale construction projects, and proposed an approach to examine organizational issues. This framework indicates how individual effort influences system efficiency: the more effort needed to build relationships, the lower the efficiency in the network.

Resolving conflicts and negotiation

Xue et al. (2005) suggested that negotiation is a necessary decision-making process to reach a consensus. Agent-based negotiation is a tool that can help resolve conflicts and balance profits among participants (Duan et al., 2012).

The agent-based algorithms used to improve negotiations can be categorized as either game-theoretic techniques, physics models, operation research models, or informal models (Kraus, 1997). Ren et al. (2003c) categorized negotiation theories into game theory, economic theory, and behavior theory, all of which inevitably overlap. Anumba et al. (2003) only suggested two categories (i.e., game theory and behavior theory). However, regardless of which category they belong to, all these algorithms are typically used to save time/cost, solve decisions, and optimize negotiation results (Liao et al., 2013).

Negotiations aim to maximize utility, called “Pareto optimality” (Yager, 2002). Many mechanisms have been designed to achieve this utility, and game theory is one of the most commonly used methods to seek strategies that satisfy participants after conflict and competition (Ren et al., 2003b). Ren et al. (Ren et al., 2003a; Ren and Anumba, 2002; Ren et al., 2002) proposed an approach for negotiating construction claims. Ren et al. (2003b) and Murray (2003) defined a concession mechanism with the principle of conflict avoidance. This mechanism implies that a negotiation will be terminated if the risks of conflict for each side are zero. However, the game theory based method was challenged by considerable research because it is based on complete information, which is not available in real-world situations (Ren and Anumba, 2002).

The game theory based method is time consuming when the number of agents increases (Kraus, 1997). This disadvantage prompted the emergence of some algorithms for large-scale agents. Kim et al. (2003) introduced a bidding mechanism, which can be established among subcontractors to trade utilities. In this system, the subcontractors can compensate one another for agreeing to changes in the schedule. This mutually beneficial arrangement is known as the "Pareto improvement" and is especially effective in mega projects. El-Adaway and Kandil (2010) introduced an approach for judging the best practice for new cases. In this technique, if the negotiator can prove that the new case is similar to a previous one, the same treatment used in the past can be adopted.

Xue et al. (2005) proposed an approach to evaluate attributes quantitatively, using an $m \times n$ evaluation matrix to illustrate m participants and n attributes. This method of evaluation can help participants clearly understand the advantages of the plans and make precise decisions during negotiations. Xue et al. (2009) eventually improved their algorithm by adopting a novel approach, that is the relative entropy method. This method was based on the information entropy model, which quantitatively evaluates the preference of negotiators for various attributes. An agent-based negotiation platform has been developed to realize this approach (Xue and Ren, 2009).

Resource and task allocation

Task allocation is often associated to a collaborative and distributed design, a complex activity requiring good communication among teams with different backgrounds. Dijkstra and Timmermans (2002) developed an agent based model to visualize the user behavior, which can support assessment of design performance. Chu et al. (2009) investigated the interaction among studies and developed a kind of MAS to obtain a collaborative 3D design in construction projects. The system includes server and client agents, assigned to accomplish specific tasks and to work separately with agent technologies. Watkins et al. (2009) developed an agent-based "bottom-top" approach which defines the efficiency of every labor activity, so that task allocation can be planned accurately.

Resource management includes money, human resources, facilities, information, and knowledge management. Most previous research in the construction domain primarily focused on tangible objects, such as money and facilities. In the recent years, however, intangible objects have drawn considerable attention, particularly those related to information and knowledge (Wu, 2001). Most the experiential information, knowledge and memory are stored only in human minds because of the subjectivity of construction data. Nonetheless, the developing complexities of projects demands the use of effective approaches to manage these subjective resources (El-Diraby and Zhang, 2006). Koo et al. (2012) proposed an intelligent knowledge management system based on MAS. The basic idea of this approach involves the integration of the individual agent knowledge management system to form a unified system. The structure of the system was developed based on loosely coupled independent agents, indicating that the system can be easily reconfigured over time when the environment changes.

Communication management

Agents can improve their consensuses through effective communication (Sycara, 1998; Yen, 2002). Obonyo (2013) claimed that communication comprises speech actions whose meanings are described by agents. Huang et al. (2006) developed a three-tier system for collaborative communication which increases system performance, security and maintainability. Trust is a crucial issue in communication management, especially when agents work separately and the environment changes constantly.

Communication technology is another research direction for MAS communication management. Traditionally, the work culture in construction industry depends on face-to-face communication. Nevertheless, with recent technological advances, wireless and inter-operative communications have become commonplace. Aziz et al. (2006) reviewed and compared intelligent wireless communication services in construction (e.g., Wi-Fi, Bluetooth and 3G), and discussed the integration with agent-based technologies to support mobile construction workers. Lee and Bernold (2008) developed a wireless system to realize "ubiquitous communications" that can link the information island together. A platform prototype was used to alert weather changes to outside workers. Lu et al. (2011) observed that although radio frequency identification (RFID) technology has significantly improved and is now widely used in various domains (e.g., retail, security, and transportation), it is yet to be commonly used in construction. These researchers illustrated several scenarios in which RFID may be used, including logistics and supply chain management, inventory management, quality assurance, access control and labor attendance records, tracking of machines and tools, and machine operations and records. Ren et al. (2011b) developed an RFID system for material planning, ordering, receiving and storing, handling and distribution, and site usage and monitoring in construction projects. Cerovsek (2011) integrated RFID with building information modeling (BIM) to automatically generate models.

Adaptation and learning issues

Learning is a basic characteristic of agents, which is the reason they are referred to as intelligent. Agents can learn from their own experience, other agents, and the environment. Alonso et al. (2001) reviewed learning in MAS and discussed it from three perspectives, namely, (1) single-agent learning and multi-agent learning, (2) on-line and off-line learning methods, and (3) logic-based learning and social learning. These researchers also cited some primary learning mechanisms, including contagious behavior, stimulus enhancement, observational learning, matched-dependent behavior, and cross-modal matching.

Some studies have investigated on the specific approaches and applications of agent-based learning. Bayesian learning is one of commonly used approaches, which can update a strategy after learning from a previous experience. Previous studies employed this technique in negotiations (Ren et al., 2003c), contract systems (Montano et al., 2008), and supply chain management (Xue et al., 2009). Agent-based learning has been adopted in some new areas in construction. Azar and Menassa (2012) introduced an agent-based learning approach for building energy performance. The agents of this system can record and learn the energy performance of individuals and then use the results to suggest various means to save energy.

Discussion

Advantages and disadvantages of MAS in construction

One of the advantages of MAS is their ability to act separately in various components of engineering or business processes, executed by numerous agents. MAS are suitable for sophisticated pattern of interactions, such as cooperation, coordination, and consensus (Ren and Anumba, 2004). In addition, MAS are robust because they do not rely on a centralized control center. Hence, the loss of one agent will not cause panic in the system. MAS can likewise disintegrate a problem into smaller ones that can be assigned to different agents for parallel processing (Shen et al., 2006b). These abilities of MAS are satisfactory for dealing with the problems that are:

1) Too large to be solved by a single agent because of limited time or resources. One of these problems is the resource-constrained scheduling problem, which is a time-consuming NP-hard optimization problem (Taghaddos et al., 2012).
2) Inherently distributed, but require collaboration and interaction (Sycara, 1998). For example, the collaborative design by individual team members (Anumba et al., 2002; Chu et al., 2009; Ren et al., 2011b), and control of a distributed sensor network in construction fields (Dibley et al., 2011; Wu et al., 2010).
3) Related to the self-interest of the participants. In the real world, most construction participants are autonomous and want to maximize their own profits. Agents could simulate negotiations, arguments, and conflicts among stakeholders and efficiently find an optimal solution (Anumba et al., 2003; Dzeng and Lin, 2004; Kraus, 1997; Ren et al., 2003c; Xue et al., 2009).

4) In a dynamic environment. Intelligent agents can learn from and adapt to the environment by themselves. Thus, MAS are adaptable to changes, which are common in construction, including design (Anumba et al., 2002), resource (Kim and Kim, 2010a), organizational (Unsal and Taylor, 2011), and schedule changes (Kim and Paulson, 2003; Kim et al., 2003; Shen et al., 2006b).

The application of MAS in construction can potentially improve the process of dealing with decentralized, complex, and dynamic problems to achieve improved efficiency, quality, and cost. However, MAS are yet to be developed significantly because of several disadvantages. The fundamental disadvantage of MAS is the ongoing debate among research communities in the areas of software engineering and artificial intelligence (Dimou et al., 2009). Such a dispute, delays the development of software. Without the support of practical toolkit for real applications, MAS are tend to act as theoretical models on paper rather than simple systems. The lack of a systematic methodology or a clear handbook, which allows people to model their applications from MAS, also hinders the development of MAS because construction problems are too complex to handle without an appropriate guide.

Future application areas

Emerging from artificial intelligence, MAS have been widely used in many other areas, such as manufacturing, transportation, information and communication, and space technology. In the construction domain, MAS have rapidly developed and have been used in almost all aspects. The applications of MAS in previous studies are listed in Table 2.

Recently developed applications of MAS should be given due attention by researchers. The first is the integration of MAS with simulation platforms, such as BIM and geographic information system (GIS). BIM, which is a collection of visualized building data, particularly in 3D modeling, has drawn significant interest recently (Cerovsek, 2011; Volk et al., 2014). Nonetheless, BIM primarily models a building without human behavior (Porter et al., 2014), which may significantly affect the building during the entire life cycle (i.e., from design and construction to operation and retrofit phase). The integration of MAS and BIM can improve the performance of the latter, given that the former can simulate human behavior in buildings and analyze the interactions of human and buildings in a virtual environment modeled by BIM. Porter et al. (2014) proposed an application of MAS in performing dynamic security analysis in a BIM environment to simulate the human behavior of attacking and defending facilities in buildings. Shi et al. (2009) proposed an agent based model to simulate the occupant behavior under fire condition. The result could improve building design in BIM. Occupant behavior can significantly impact the energy consumption of building (Hong et al., 2015). Integrated with energy plus and BIM, agent based model can predict the energy consumption more accurately (Azar and Menassa, 2012). Cambeiro et al. (2014) developed an application for multidisciplinary, integrated, and collaborative work among agents to integrate all of them in different phases with MAS, supported by BIM. These studies confirmed that, the assimilation of BIM with MAS can be used to develop additional realistic models and perform more analysis. MAS can also facilitate GIS to simulate the influence of human behavior on urban development (Zhang et al., 2013).

The second new application of MAS is information and knowledge management, particularly big data management. The growing trend of big data management, including data mining and cloud architecture, indicates that massive amounts of historical data can already be stored, processed, and shared (Fiosina et al., 2013). However, the dataset can be exceedingly large to be processed by a single processor (Bianchi et al., 2013). On the one hand, the decentralized characteristic of MAS can process data separately by avoiding the transmission of big information volumes, particularly with cloud computation (Fiosina et al., 2013). On the other hand, big data can offer a powerful computing infrastructure for MAS applications for modeling and simulation. MAS can help collect of huge amounts of data from individuals and apply data mining results to individuals (Gao and Cho, 2012). Although related research has emerged in other domains, the applications in construction have received inadequate attention. MAS integrated with big data can provide decentralized, cooperative, and networked systems. These systems are suitable for addressing sophisticated problems in construction, such as preference analysis (Gao and Cho, 2012), decision support (Bianchi et al., 2013), and strategy optimization (Fiosina et al., 2013).

Thirdly, MAS have been employed in applications related to green building, especially to the energy efficiency of buildings (Azar and Menassa, 2010; Zhang et al., 2010). Different behaviors of occupants can affect the energy consumption of buildings by more than 150% compared with the simulation benchmark (Clevenger and Haymaker, 2006). Although the occupants significantly affect the energy consumption in real-life situation (Yang and Wang, 2013), the actual energy simulation platforms disregard occupiers' behavior (Hoes et al., 2009). MAS can enhance the performance of traditional energy simulation platforms, (e.g., Energy Plus), by integrating the characteristics of the occupants (Azar and Menassa, 2010; Hong et al., 2015; Kashif et al., 2011). To achieve effective energy and comfort management in a building environment, intelligent control systems have been developed based on MAS (Klein et al., 2012; Lee and Malkawi, 2014; Yang and Wang, 2013; Zhang et al., 2011). These systems are user-oriented and can simulate building occupant interaction. Therefore, the systems can simultaneously manage energy efficiency and user comfort. For example, the occupants can adjust their behaviors on window use, blind use, and space heater/personal fan use. These behaviors can change the comfort level of occupants and the electricity consumption of the building (Lee and Malkawi, 2014).

Finally, a potential application of MAS is to improve management efficiency in construction site. Construction site is very complex, which involves various construction workers with different tasks assigned, equipment, materials and environmental constraints (e.g. rain, snow, wind). MAS could simulate the behaviors of construction workers and their interactions with tasks, equipment, materials and environment. An agent-based system was developed to simulate the traffic flow of construction equipment in construction site (Kim and Kim, 2010b). It is advanced compared to traditional discrete simulation, since the MAS can adapt to the highly dynamic environment and uncertainty in construction operation (Mohamed and AbouRizk, 2005). In addition, MAS can be used to model and simulate constructions workers, whose attitudes and behaviors directly affect a construction project's performance (Ahn and Lee, 2015). Based on the simulation results, related interventions can be developed to improve site management (e.g. improving workers' efficiency, reducing absenteeism).

Development and prospects

The process of developing solutions for theoretical and practical problems in construction is illustrated in Figure 4. The process is iterative (Ren and Anumba, 2004). The specific industry problems should first be identified and divided into sub-problems (e.g., stakeholders and procedures). MAS are then modeled by abstracting characteristics, defining constraints, quantifying, and mapping the model. After modeling, algorithms and mechanisms should be developed to address the problem. MAS are then implemented using appropriate software and platforms. The specific problems should be resolved based on MAS. Nevertheless, new problems may emerge after validation and evaluation. Thus, the development process should be run again to develop MAS that are adaptive to real situations. The key issues of MAS identified by this study can offer solutions and contributions to every step of the process. Beyond the internal iterative development process, external areas (i.e., theoretical model of MAS, development trends of construction, and advanced applications of MAS in other domains) can likewise improve the process.

Based on the development process, new approaches have emerged and technologies have been continuously updated. In the future, the following directions may require further attention.

System robustness under uncertainty: Construction projects are subject to strict deadlines, budgets, and resource constraints. Thus, traditional approaches can potentially crash when changes are applied. MAS can be used under these conditions because they can adapt easily to new situations. Despite being dynamic, MAS are not designed for uncertainty. Future MAS should focus on uncertainties when simulating the environment and human behavior, including the stochastic process or other probability distributions.

Real-time management: Numerous emergencies may arise in construction projects, including natural (e.g., weather changes, earthquakes, floods, and hurricanes) and human causes (e.g., contract breaches, political reasons, accidents, and supply delays). Most of these emergencies cannot be predicted, and may thus result in inestimable losses. Therefore, real-time management is important for construction, through which real-time communication, processes, and control can be achieved. With their parallel process ability, MAS can provide the necessary support to this direction.

Integration with modern algorithms and approaches: MAS is a framework that has been previously integrated with game theory, Bayesian learning, genetic algorithm, and ant colony algorithm. However, several agent-related algorithms and approaches have been developed in the last decades. Some of methods are widely used at present, but only a few of them are adopted in the field of construction. For example, the Laplacian-based consensus algorithm has recently been developed and used in various areas. Nevertheless, few studies have employed this framework in construction. Therefore, modern approaches should be followed and adopted in this field.

Development of software and toolkit for real projects: To date, different simulation software have been applied in different contexts to develop MAS applications. Commercial off-the-shelf (COTS) software is commonly used in general applications. For example, JADE (Chu et al., 2009) and ZEUS (Xue et al., 2005) specialize in handling logic among agents, NetLogo (Andrews et al., 2011) and Anylogic (Azar and Menassa, 2012) specialize in graph and 3D demonstration. In addition to COTS software, various agent-based algorithms, systems, and platforms are customized for actual projects, such as e-HUBs (Ren and Hassan, 2007), virtual organizational imitation for construction enterprises (Du and El-Gafy, 2012), and supply chain simulator (CS2) (Min and Bjomsson, 2008). Nonetheless, MAS continue to be difficult to use in real-life situations (Dimou et al., 2009) because of the aforementioned disadvantages. Most software and toolkits are on the simulation stage than on practice because of the limitations in dealing with complex projects. The further development of MAS should be directed toward real project applications for MAS to become empirical.

Conclusions

"Collaboration and consensus" are identified as a key success factor in construction in which fragmentation is a serious problem. However, this factor is difficult to attain because of inherently distributed problems, self-interested participants, and dynamic environment in construction. MAS naturally support such problem because of the autonomous, cooperative, and learning behavioral attributes of agents. Orienting this problem, this study analyzes how MAS are applied to improve collaboration and consensus in construction.

The development of MAS in construction occurs iteratively in three steps, namely, problem identification and composition, problem abstraction and modeling, and MAS implementation and validation. The issues identified in this study can support all these steps. Assistance from external areas can inspire and improve MAS development in construction. In comparison with related studies in different domains, several advanced methods, platforms and applications of MAS are addressed and introduced to the construction industry.

In previous studies, MAS were mainly applied to scheduling, dispute resolution, decision support system, and collaborative design. Apart from these traditional areas, new applications are suggested in this review, including BIM, GIS, Energy plus, knowledge management, energy performance simulation and site management. The efficiency of MAS in modelling interactions of human and environment is advanced in certain applications (e.g., human influence on energy consumption). The applications of MAS remains limited, and further innovative areas should be explored in the future.

Given that considerable research has been made, the construction industry not only uses MAS as a tool, but it continuously contributions to MAS development as well. For example, Anumba et al. developed a collaborative design of structures by using intelligent agents

(Anumba et al., 2002). This method has been cited and applied in computer science domain. Xue et al. (Xue et al., 2005) proposed an agent-based framework for supply chain coordination in construction, that influences the areas of manufacturing, information, and economics. MAS have been applied in construction for decades, but some of their disadvantages and crucial problems remain unaddressed. In addition, the majority of studies on MAS have focused on frameworks, algorithms, and simulation than on their applications in real projects. From the industry perspective, the agent-based technology is generally considered a “nice-to-have” tool but not a “must-have” (Shen et al., 2006a). Therefore, substantial efforts should be achieved before MAS can be widely used in construction.

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