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An Agent-Based Framework to Improve Coordination in the Process of Urban Infrastructure Provision in Iran

Saeid Yazdani[1, 2, *], Mohd Johari Mohd Yusof[1], Mohammad Mehdi Azizi[3], Abang Abdullah Abang Ali[4]

[1]Department of Landscape Architecture, Faculty of Design and Architecture, Universiti Putra Malaysia, Serdang, Selangor, Malaysia
[2]Department of Urban Planning, Malayer Branch, Islamic Azad University, Malayer, Hamedan, Iran
[3]School of Urban Planning, College of Fine Arts, University of Tehran, Tehran,Tehran, Iran
[4]Housing Research Centre, University Putra Malaysia, Serdang, Selangor, Malaysia

Abstract

Urban infrastructure systems are basic requirements for civilized societies all over the word. The ever increasing reliance of modern society on these interconnected urban sub-systems triggers great attention about the provision of urban infrastructure systems. In turn, coordination between different agencies, who are involved in the process of urban infrastructure for new areas, plays a prominent role in the success of the process. The essential need for coordination in the process of urban infrastructure provision is derived from three different sources, complex nature of infrastructure systems, the existence of multiple interdependencies between these systems, and triple role of human beings in the process.To this end, based on findings of coordination context of urban infrastructure provision in Iran, coordination theory, and agent-based modeling approach, this paper presents an agent-based modeling framework in order to improve coordination between different urban infrastructure agencies in the context of service provision for new residential areas.

Keywords

Urban Infrastructure Provision, Coordination, Interdependency, Agent-Based Modeling

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1. Introduction

Urban infrastructure systems are essential to social well being of cities and their economic prosperity. They constitute urban physical structures, including municipal water supply system, transportation (road, rail, water), energy systems (electric power, natural gas, oil), Sanitation, and Communications. Urban infrastructure systems are large scale socio-technical systems that facilitate urban activities. These essential structures are complex networks, geographically dispersed and defined as nonlinear systems which interact with one another, their surrounding environment and well as, with human as owners, operators and users (Amin, 2002b). Furthermore, the presence of a large number interdependencies such as physical, geographical, cyber, and logical interdependencies (Rinaldi et al., 2001), among them has significantly augmented the complexity of the whole urban infrastructure system.

Adequate provision of urban infrastructure is the foreground once we speak [sustainable] city development and the quality of life in cities. In the absence of urban infrastructure, land has no potential for development (Porter, 1986), and urban expansion leads to slum dweller areas (Otegbulu & Adewunmi, 2009). Urban infrastructure provision (hereafter,

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* Corresponding author
E-mail address: saeedyazdani110@yahoo.com (S. Yazdani)

referred to as UI-provision) is a prolonged process; comprising planning, financing, construction and renovation that involve a multitude of organizations (Wu, 1999). Coordination among and between these different organizations (hereafter, referred to as urban infrastructure agencies or UIAs, such as, water and wastewater agency, electricity agency, transportation agency, etc.) is a striking challenge that jeopardizes the success of UI-provision worldwide (Yazdani et al., 2015). In consistence with this, Sohail et al. (2005) point out that duplication of functions, overlap of responsibility, and lack of coordination between different UIAs are common constraints for efficient UI-provision in developing countries.

In Iran, like most of the developing countries, authority and responsibility of the three main stages of UI-provision Planning, Financing and Implementation (Liu, 2004) are dispersed among several organizations, both vertically and horizontally. This fragmentation of authority and responsibility result in limited inter-sectoral relationships and subsequent lack of coordination between different UIAs (Hejazi, 2003). In the other words, urban infrastructures are not treated as interconnected systems, but rather being designed and constructed independently. Lack of coordination between different UIAs in the process of UI-provision in, Iran like other developing countries, yields a number of problems such as overlapping and duplication of activities (Khan, 1997), failure in meeting project deadlines (Panday & Jamil, 2010) and so forth. Hence, sound coordination between UIAs is a core key to achieve prosperity in the context of UI-provision for new residential areas.

Two predominated features of urban infrastructure systems, their inherent complexity and exhibited interdependencies, make coordination between UIAs to be a pivotal aspect in the process of UI-provision (Yazdani et al., 2015). The intrinsic complexity of urban infrastructure and pertinent decision makings can be explained and formalized by means of complex system theory (Holland, 1988) and its direct branch, agent-based modeling approach. On the other side, the exhibited interdependencies between urban infrastructure and corresponding organizations, UIAs, can be managed by means of coordination theory (Malone & Crowston, 1994). To this end, based on these two well-known theories and the findings of two case studies in Iran, we present an Agent-Based modeling framework for improving coordination during the process of UI-provision for new residential areas.

Agent-Based Modeling (ABM) as a logical tool (Sanford Bernhardt & McNeil, 2008) and insightful mindset (Bonabeau (2002), with its demonstrated success in dealing with complex and interdependent process such as urban infrastructure management (Davis, 2000) has a great potential to offer insights into why UIAs' activities are not coordinated. And how UIAs can better coordinate their activities in the favor of successful provision of infrastructure for new residential areas.

In general, this paper presents an Agent-Based Model as a framework to improve coordination between different UIAs in the context of UI-provision for new development areas. The remainder of the article is structured in the following format: the next section presents a systematic literature review of complex system science and agent-based modeling. In Section 3, from an urban infrastructure-centric point of view, a comparison between agent-based modeling paradigm and other modeling approaches is presented. Section 4 covers rationales beyond applying ABM in urban infrastructure topics. Then, section 5 discusses about the essence of coordination in urban infrastructure provision. The research methodological steps are described in section 6. The heart of the article is presenting an agent-based modeling framework introduced in section 7. Finally, conclusions are presented in Section 8.

2. Complex System Science and Agent-Based Modeling

2.1. Complex System Science: a Conceptual Overview

Complex system can be defined as a system or system of systems made up of many interacting components (Mitchell & Newman, 2002). Complex systems demonstrate behavior which is different from the sum up the individual part behaviors. In the other words, they exhibit *emergent behavior*, arising from the interactions among their parts. Bak (1996) points out that *emergent behavior* cannot be explained exclusively by the sum of the complex system's component behaviors. He also considers systems with large variability as complex systems. However, considering the fact that urban infrastructure systems do not function as isolated segments, but rather as interconnected networks, as well as considering their emergent behaviors, it can be concluded that they should be respected as complex systems. Therefore, complex system theory and its direct branch, Agent-Based Modeling, can offer a promising way to explain their variability and the sometimes unpredictable behavior of urban infrastructure systems.

A complex system is a collection of inter-related parts wherein the simple actions of the basic element or agents would be combined in unplanned ways which result in unforeseen results. These elements or agents, in any case, respond to other agents as well as their surrounding environment in which they work. Complex system science is comparatively a new field of research pertinent to understanding systems which are characterized by self-organization, nonlinear behavior, feedbacks, emergent behavior, and irreducibility (Baynes, 2009). Complex system concept cuts across the borders between different branches of the sciences. This notion makes use of thoughts, approaches, and examples of various disparate disciplines. Therefore, its outcomes have a great capability to be applied in different scientific and engineering dilemmas. In the same vein, Bar-Yam (1997) argues that the principles of complex systems may be applied to solve disparate problems ranging from particle physics to the economics of societies.

Complex system approaches clearly explain the behavior of the constituents from the bottom up. More significantly, complex system approaches capture the interactions among the constituents with one another and as well with their surrounding environment. The features of complex systems and pertinent theories have been demonstrated by several authors inter alia, Gall (2002), Barabasi (2002), Sanford Bernhardt and McNeil (2004), and Miller and Page (2007). For instance, Sanford Bernhardt & McNeil (2004) itemize four characteristics for complex system: (1) Multiple Agents; (2) emergent behavior; (3) System states; and (4) interconnectedness. Another notable vision on complex system has been presented by Gall (2002): “A complex system that works is invariably found to have evolved from a simple system that worked. The inverse proposition also appears to be true: A complex system designed from scratch never works and cannot be made to work. You have to start over, beginning with a working simple system.” However, the most cited demonstration of complex system theory has been offered by John Holland (1988), a pioneer in the field. Holland enumerates four striking features for complex system: (1) many decision makers or agents with dispersed control; (2) many organizational levels; (3) the ability of agents to adopt; and (4) the use of internal models to anticipate the future.

Agent-Based Modeling, with its direct root in complex system sciences (Weisbuch, 1991), is an emerging approach for modeling and explaining the complex process such as process of urban infrastructure provision. According to Macal and North (2010), Agent-Based Modeling (ABM) is a comparatively new approach for explaining and modeling complex systems which are composed of interacting components or agents. To this end, in the following sections an overview of ABM and related concepts are presented.

2.2. Agent-Based Modeling (ABM)

Agent-Based Modeling is a potent tool which offers a bottom-up understanding of complexity in decision-making process and solving complex problems, by definition, three features of complex problems are: multi-scale, multi-perspective, and multi-actor (Gilbert & Terna, 2000). ABM is one modeling method pertinent to evolutionary theory which has been developed in the domain of complex system research (Mitchell & Newman, 2002). Bonabeau (2002) stress that ABM is a mindset more than a technology. Agent-Based Modeling mindset describes a system from the standpoint of its component units. ABM as a simulation approach as well as a modeling paradigm offers an immense improvement to the understanding of complex systems as such urban infrastructure systems (Wolfram, 2002). In consist with this notion, Epstein and Axtell (1996) point out that ABM may change the way we think about the explanation of complex process such as urban infrastructure provision process. In line with this, by quoting Jennings et al. (1998, p. 7): “The agent-based view offers a powerful repertoire of tools, techniques, and metaphors that have the potential to considerably improve the way in which people conceptualize and implement many types of software.”

However, Agent-Based Modeling is known by a number different names: ABS (agent-based system or simulation), IBM (individual-based modeling), ABM (agent-based modeling), multi-agent system (MAS) and ABMS (agent-based modeling system or simulation). Agent-Based Modeling is an up-and-coming approach to modeling complex processes and a reliable solution for solving complex problems. Its origin is traced back to the beginning of the 1940s, when the first prototypes “cellular automata” was formulated. Notwithstanding its long history, it was only the 1990s that ABM paradigm became conceptually and computationally grown-up to be employed in science and academic research (Chen, 2012). The roots of ABM can be found in the investigation into complex systems (Weisbuch, 1991), artificial life (Langton, 1989), and complex adaptive systems (Holland, 1995). But ABM is not just tied to understanding and designing “artificial” agents (Macal & North, 2006). The main roots of ABM can be traced back into modeling organizations and human being's behavior and individual decision making (Bonabeau 2002). However, Agent-Based Modeling approach leans to be descriptive, with the aim of modeling the behavior of individuals, rather than normative resembling traditional research, which attempts to identify and optimize optimal behaviors (Macal & North, 2010).

ABM is a computational technique to model individual behaviors of agents (autonomous entities) and their interactions. Mitchell and Newman (2002) argue that the phrase “Agent-Based Modeling” refers to a set of procedures in which autonomous entities and their interaction are clearly modeled, and also emergent behaviors can be captured. Agents in ABM can range from social entities such as organizations and people to autonomous robots; and from biological entities such as birds, plants, and animals to physical entities such as molecules and atoms. Based on a set of interaction rules and predetermined characteristics, in Agents Based Modeling, agents interact with one another and surrounding environment (Sanford Bernhardt &McNeil, 2008). Every agent individually assesses its condition and makes decisions upon a set of rules (Bonabeau, 2002). Agents possibly will perform a variety of behaviors in order to represent the pertinent system. Each agent has its own properties and act based on available information. To reiterate, in ABM, the components of the system are presented as agents with specific features such as abilities to adapt and interact with other agents and surrounding environments. Macal and North (2008) argue that an ABM, in general, is a model in which agents interact repeatedly. For instance, once agents optimize their behaviors through simple exchanges of information, the purpose is to realize a preferred end-state rather than to simulate a dynamic process for its own sake. Therefore, the goal of ABM is to scheme models which are adequately simple that the mechanisms of emergent behavior in complex systems can be understood and yet elaborate enough to show interacting behaviors (Mitchell & Newman, 2002).

ABM in its standard form consist of a set of "Agents" communicating by sending messages to one another through an "Environment" (Gilbert & Terna, 2000). Usually the agents and the environment are presented in Toolkit softwares such as Swarm (Minar et al., 1996), MASON (GMU, 2006), NetLogo (NetLogo, 2006), and Repast (North et al., 2006). Mostly the environment, in Agent-Based Modeling, is simulated as a two dimensional space and each agent is positioned in a different location. Wooldridge (2002), one pioneer in the field, defines an agent as a physical or logical (semi-) autonomous entity, and ABM as an organic and systematic society comprising agents to provide functions. In the words of Luck et al. (2003), ABM consists of interconnecting agents who autonomously elaborate information and resources in order to define their outputs which latter became inputs for other agents, and so forth. These independent agents may be heterogeneous and might represent mobile actors, such as animals, people, companies, or even industries. However, because of several reasons ABM is becoming prominent, especially in the domain of urban infrastructure: First, the systems, such as urban infrastructure systems, which are necessitated to be analyzed and modeled, are becoming more and more complex because of their interdependencies. Second, our data are becoming systematized into databases at finer levels of granularity, Micro-data can now support micro simulations. Third, some systems are too complex to be adequately modeled by conventional methods. Finally, computational power is progressing speedily.

2.3. ABM Application

Agent-Based Modeling paradigm is a logical tool for improving our understanding of complex physical and social phenomena. According to Axelrod and Tesfatsion (2010) ABM offers a methodological approach that permits two significant improvements: (1) the precise examination, modification, and extension of existing theories which have been proved to difficult to evaluate and formulate using mathematical and statistical method; and (2) a profound understanding of fundamental causal mechanisms in multi-agent systems whose study is presently separated by artificial disciplinary boundaries. These significant ABM's capabilities result in a wide range of ABM applications, from small, elegant, minimalist models to large-scale decision support systems. Bonabeau (2002) categorizes ABM applications in four main areas: organizational simulation, market simulation, diffusion simulation, and flow simulation. The application of ABM range across a broad continuum, from minimalist models to large-scale decision support systems.

ABM, indeed, has been applied to a wide range of topics, ranging from biology to geographical resources management. One of the first ABM applications in biology, studying the formation of insect colonies, has been introduced by Hogeweg and Hesper (1983). Similarly, it has been used in the simulation of modeling behavior (Reynolds, 1987) and the motion of crowds (Batty 2005; Saunders & Gero 2004). In the context of ecosystem and environmental management, ABM is even more fashionable. Lansing and Kremer (1993) were among the opening researchers who applied ABM in water resource modeling. Their work offered a new perspective for modeling of water-related scenarios which has been influential by the now (Feuillette et al., 2003). In association to water resource managements, this kind of modeling paradigm also has been utilized into forestry (Hoffmann et al., 2002) and agriculture (Parker & Meretsky, 2004; Berger, 2001).

In social and urban related science, the use of agent-based modeling, in comparison to other domains of knowledge, is more common. The first social ABM was formulated by Sakoda (1971), the Checkerboard Model, his model was based on cellular automaton. Similarly, Schelling (1978) expands an ABM for modeling housing segregation, where agents represent homeowners and neighbors. In his model, interactions of agents represent agent perceptions of their neighbors. The Schelling's model has illuminated the way for the application of ABM in pertinent fields over since Chen (2012). In the same vein, Drogoul and Ferber (1994) offer an agent-based model for dealing with emergent phenomena in cities. Using this modeling paradigm, residential dynamics in cities have been formulated by Benenson (1999) and also, similarly, by Kohler and Gumerman (2001). Land use change in cities has been modeled by using this modeling approach (see, for instance, Rindfuss et al., 2008; Kii & Doi, 2005). However, it would be worth to mention that developing of geographic information system (GIS) has paved the way to use ABM increasingly in urban related affairs (see, for example, Jiang & Gimblett, 2002; Brown et al., 2005; Brown & Xie, 2006).

ABM is a logical tool for improving our understanding of urban infrastructure systems. Considering its successful application in modeling complex systems and also the fact that urban infrastructures are complex systems, ABM offers a great potential to model urban infrastructure provision and management. One of the first ABM applications in urban infrastructure was the simulation of the size-frequency distribution of traffic jams (Nagel & Rasmussen, 1994). In the later step, Fischer et al. (1996) developed an ABM to model transportation scheduling and management. Tillman et al. (1999) developed an agent-based model in order to model the interactions between different stakeholders (politicians, users, engineers, operators, etc.) to better understand the implications of public policy pertinent to water resource management in Swiss cities. CISIA is an ABM pertained to infrastructure systems developed by Panzieri et al. (2004). This model is useful to analyze fault propagation across heterogeneous infrastructures. As another example of ABM applications in Urban infrastructure affairs, Sanford Bernhardt and McNeil (2004) offered a model which presents insights into network-level behavior of urban infrastructure systems, using a simple simulation of pavement segments as agents. Cirillo et al. (2006) set up an agent-based model devoted to the electric power market which called The EMCAS (Electricity Market Complex Adaptive System). Their model designed to investigate electric power market restructuring and deregulation. The decisions of users and system operators during a water pollution occasion has been modeled, using agent-based modeling paradigm, by Zechman (2011). One of the salient ABM applications in urban infrastructure management has been developed by Osman (2012). He adopted an agent-based model as a framework to capture the complex interactions occurred within the context of urban infrastructure management.

3. ABM vs. other Modeling Approaches: From an Urban Infrastructure Perspective

Agent-based modeling is a logical approach which can explicitly model the interdependent and complex nature of urban infrastructure systems. Urban infrastructure systems exhibit interdependencies among themselves and their environments, including physical, financial, organizational and political environments. One of the salient advantages of ABM over other modeling paradigms, such as mathematical models, is its capability to capture and explain the interactions between systems and their surrounding environments (Grimm et al., 2006). Moreover, the complexity feature of urban infrastructure, which could not be recognized by conventional model, can clearly be demonstrated and modeled by ABM (Sanford Bernhardt & McNeil, 2004). Consistent with above mentions, Amin (2002a) stresses that “the conventional mathematical methodologies that underpin today’s modelling, simulation and control paradigms are unable to handle the complexity and interconnectedness of these critical infrastructures”.

As well, ABM defines urban infrastructure systems from the bottom up, in contrast to conventional aggregate models, by perusing the behavior of their component units- the agents. To wit, the social and autonomous features of agent, in ABM, pave the way to model the nonlinear interactions between urban infrastructure systems. Secondly, according to De Smith et al. (2007), in any given system environment an ABM can be defined as well as works on different levels of abstraction. Thirdly, ABM is flexible (Bonabeau, 2002). ABM flexibility can be seen along several dimensions. As such, it offers a framework for adjusting the complexity of agents: ability to learn, behavior, rationality, and interactions’ rules. Furthermore, in a given ABM it is possible and easy to add some new agents. The agent’s ability to change levels of aggregation and explanation can be considered as another flexibility dimension of ABM. Nevertheless, the striking feature of Agent-based modeling is that the interaction among agents via an agent communication language (Tian & Tianfield, 2006) enables urban infrastructure agencies to negotiate and coordinate their work with each other more efficiently in the context of the UI-provision.

However, notwithstanding of its prominent capabilities, ABM has raised a number of criticisms. Grimm et al. (2006) numerate two major and interconnected drawbacks for ABM: (a) ABMs are more often described verbally without an evident mention of the rules, equations which are applied in the model. (b) There is no standard protocol for describing them. It has been claimed that the most common negative aspect of ABM is that its outcomes are not easy to assess. This problem is bipartite. First, the ABM’s heterogeneity results in a rich context of variable parameters. So that ‘‘even if its output matches reality, it’s not always clear if this is because of careful tuning of those parameters, or because the model succeeds in capturing realistic system dynamics’’ (Buchanan, 2009). Second, there is a concern about its validation. As, Axelrod (1997) argues that ‘‘whether the unexpected result is a reflection of a mistake in the programming, or a surprising consequence of the model itself’’ (p. 210). In the same vein, Kikuchi et al. (2002) point to the fact that ‘‘…the individual agents do not make the globally optimal decisions’’ (p. 13). Additionally, it is worth to mention that this modeling paradigm is a high cost, time-consuming and complicated process.

To summarize, in spite of criticisms raised on ABM, its advantages over other modeling paradigms have been captured in three declarations by Bonabeau (2002): (1) ABM offers a natural explanation of systems such as urban infrastructure systems; (2) ABM is flexible; (3) emergent behavior can be captured by ABM. However, it is evident that its capability to deal with emergent phenomena arising from individual actions and interactions in complex systems (such as urban infrastructure system) is what triggers other benefits.

4. Rationales Beyond Applying ABM in Urban Infrastructure Topics

Complex systems theory and its direct branch, ABM, are promising method for modeling urban infrastructure provision process as it prognosticates decision-making environment (Sanford Bernhardt & McNeil, 2004) as well as it simulates the behavior of interacting and adapting agents who are involved in the process. The development of urban infrastructure is evolutionary and intractable process (Dennet, 1996). In the other words, the exact future of this developing procedure can never be totally projected. Nikolic and Dijkema (2010) argue that the only reliable way to forecast the future state of an evolutionary system is to carry out an action and scrutinize its consequences over time. ABM, as a powerful computational technique (Bonabeau, 2002; North & Macal, 2005), is able to simulate the effects of actions in the evolutionary process, such as UI-provision. However, the rationales beyond applying ABM in urban infrastructure-related studies can be summed up as followings.

The complex nature of urban infrastructure systems can be captured via agent-based modeling approach. Urban infrastructure systems have been identified as complex systems by several scientific authors (see, for example, Levinson & Yerra, 2006; Yerra & Levinson, 2005; Amin, 2002b; Heller, 2002). According to Jiang and Tianfield (2006), ABM is a way to understand the behavior of complex systems, especially their emergent behavior. By definition, in complex systems such as urban infrastructure systems the individual parts (called components or agents) and their interactions result in large-scale behaviors, or so-called "emergent behavior", which cannot be simply projected from a knowledge only of the behavior of the individual agents (Mitchell & Newman, 2002). Agent-based modeling approach can handle both micro and macro level aspects of complex systems. In the words of Macal and North (2010), one of the most substantial characteristics of agent-based modeling is its ability to model complex systems such as urban infrastructure systems. Hence, in point of fact, the most suitable approach to model complex system (such as urban infrastructure) is the use of ABM (Panzieri et al., 2004).

The interdependencies between urban infrastructure systems can be modeled by means of ABM. According to Rinaldi et al. (2001), urban infrastructures are exceedingly interconnected and mutually interdependent. ABM has the capability to capture and model the interdependencies between urban infrastructure systems. De Smith et al. (2007) argue that ABM is suitable for modeling complex interactions between heterogeneous agents. However, based on a set of interaction rules, in ABM, agents interact with each other and their environment. In agent-based modeling, interactions among agents can take a variety of forms, these interactions can be symmetric or asymmetric (Mitchell & Newman, 2002). To wit, in the words of Macal and North (2010), ABM puts forward a way to model systems such as infrastructure systems who are interdependent and influence one another. Hence, the ever-increasing interconnectedness of urban infrastructure systems (Sanford Bernhardt & McNeil, 2004) and the capability of ABM in modeling systems' interdependencies would justify its application in urban infrastructure studies.

ABM offers a bottom-up approach for understanding the complex consequences of decisions in urban infrastructure management. The bottom-up evolutionary nature of urban systems, especially infrastructure systems, been recognized by several urban-scientist (see, for example, Jacobs, 1961; Baynes, 2009). Conventionally, urban infrastructure systems have been modeled via top-down approaches such as network level optimization (Hudson et al., 1997), system dynamics (de la Garza et al., 1998), and input output analysis (Haimes & Jiang, 2001). In contrast, agent-based modeling approach frames systems, like urban infrastructure systems, from the bottom up, by investigating the behaviors of their component units (Chen, 2012). By definition, ABM as a modeling paradigm presents a grand improvement in the understanding of the overall behavior of infrastructure systems, resulting from evolutionary actions. Overall, the bottom-up nature of ABM makes this paradigm to be an effective technique for modeling urban infrastructure systems.

Its distinguishing features make ABM to be an appropriate paradigm for modeling urban infrastructure system. In contrast to traditional modeling approaches, following features makes ABM to be a salient modeling technique. Agents, in ABM, have unique properties such as reactivity and pro-activeness, social ability, and autonomy (Wooldridge & Jennings, 1995). In the words of (Hayes, 1999), social ability means agent is part of the community as well as it is able to interact with other agents in order to accomplish its duty. Autonomous capability implies that agents are able to carry out instructions and make decisions autonomously, without direct intervention of others, and also they have control over their accomplishments and states (Castelfranchi, 1995). Furthermore, according to De Smith et al. (2007), within any given environment ABM can be defined. As an another distinguished feature of ABM, there is an ontological correspondence between real world actors and the computer agents in the model which makes it simple and clear to represent actors and their environment as well as the relationship between them (Gilbert, 2008). Finally, Macal and North (2010) point out that the self-organization and the stress on the heterogeneity of agents across a population can be enumerated as other features of ABM.

To sum up, topics in urban research, especially urban infrastructure systems, are possibly among the most complex ones (Chen, 2012), since they involve social and technical aspects and also temporal and spatial interactions among different stakeholders. Considering the distinguished feature of ABM, as mentioned above, this modeling paradigm paves the way to model urban infrastructure systems that are composed of agents who interact with one another and adapt their behaviors in order to be better fitted to their environment. To reiterate, by quoting Axelrod and Tesfatsion (2006), ABM is an appropriate technique for urban infrastructure aspects where “the system is composed of interacting agents” and “the system exhibits emergent properties, that is, properties arising from the interactions of the agents that cannot be deduced simply by aggregating the properties of the agents.”

5. The Essence of Coordination in Urban Infrastructure Provision

Urban infrastructure systems are essential for city development and quality of life. Feldman et al. (1988) argue that vibrant urban infrastructures are pivotal factors for the prosperity of urban community. In the absence of these essential systems land would have no potential for any kind of urban developments. Along the same track, Porter (1986) points out that infrastructure systems are vital elements for any development, that is why without them development will not occur. In the same vein, Engel-Yan et al. (2005) point out that in order to achieve sustainable urban development, those who are involved in urban design process must consider the unique role of urban infrastructure in urban shaping. Therefore, it could be concluded that provision of urban infrastructure is prior to any urban development activities.

Worldwide, numerous approaches being applied in UI-provision, but three phases are common in all of them; Planning, Financing and Implementation (Liu, 2004). Responsibilities of these three phases, usually, are dispersed across various organizations. Dispersion of responsibilities, in turn, demands sound coordination between and among organizations who are responsible for the UI-provision. Absence of coordination poses a striking challenge to those involved in the aforementioned phases, who come to UI-provision process from different perspectives (Tornberg, 2010), experience different institutional barriers to policy integration (Stead, 2008), and rely on different kinds of knowledge. Along the same track, Siddique (1994) enumerates a number of reasons in the favor of the importance of coordination among urban infrastructure agencies. Firstly, coordination would lead to the pooling and sharing of financial resources, expertise, and experience. Secondly, it could be applied for standardizing and optimizing services. Thirdly, coordination motivates joint projects. Fourthly, coordination would pave the way for recognizing and resolving common problems. Finally, coordination enables UIAs to handle their existing peripheral conditions.

Urban infrastructure provision is complex and exceedingly complicated process (Sözüer & Spang, 2012). The inherent complex nature of UI-provision results from several factors. First, urban infrastructure systems are interconnected and mutually dependent in complex ways (Heller, 2002; Little, 2002). To wit, what happens to one of these kinds of urban systems would directly and indirectly affect other systems. Second, several agencies at multi level of decision making are involved in the process of UI-provision (Wu, 1999). It is evident that different stakeholders involved UI-provision process makes it to be more complex. Third, urban infrastructures are geographically dispersed systems which are interacting with human beings (Sanford Bernhardt, 2004), as constructors, operators, and users. Forth, According to (Sözüer & Spang, 2012), deficiencies resulting from urban infrastructure agencies’ shortcoming exacerbate the complexity feature of the UI-provision.

Considering complex system features, which being characterized by John Holland (1988), urban infrastructure provision can be and must be treated as a complex process. According to Holland, these characteristics are as followings. First, many autonomous agents involved in the process. In the domain of UI-provision these autonomous agents are Water Co., Electricity Co., Gas Co., systems’ user, etc. second, multiplicity of organizational levels. Organizations at different levels (city, province, and national) are involved in process of UI-provision. Third, the capabilities of agents to adapt. Urban infrastructure agents adapt to the situation of urban infrastructure and resources at their disposal (Sanford Bernhardt & McNeil, 2004). Forth, the utilization of internal models to forecast the future. Anticipating the future needs these facilities by infrastructure planner. Furthermore, Chunlei et al (2011) enumerate some other complexity features UI-provision: (1) *Openness.* Urban infrastructures are open system; interchanging material, energy, and information with one another as well as the surrounding environment. (2) *Multilevel.* Urban infrastructures cover all aspects of urban life, including potable water, energy, power, transportation, etc. (3) *Dynamic non-equilibrium.* Many categories of facilities are involved in infrastructures. (4) *Nonlinear.* Each one of urban infrastructure can influence others and be affected by other kinds at the same time. (5) *Dynamic non-equilibrium.* They have the dynamic characteristic and as well, continuity features.

The complex nature of UI-provision makes coordination to be a core aspect in the provision of these vital urban structures. In the same vein, Kjenstad (1998) points out that there is an essential need for coordination in complex cooperative processes such as UI-provision. Nevertheless, the multiple role of human beings in the process of UI-provision (as system provider, operators, and users) intensify the requirement of coordination in these kind of complex process (Mintzberg, 1993). Consistent with Mintzberg's statement, Sanford Bernhardt (2004) argues that the involvement of humankind in the urban infrastructure provision exacerbates the needs for coordination among different agencies who are involved in the process.

As well, urban infrastructures are interdependent systems. This interdependent nature, in turn, makes coordination to be an essential factor in the process of provision of them. The interdependent nature of these urban systems has been identified and stressed by several scientific authors (see, for instance, Engel-Yan et al., 2005; Sanford Bernhardt & McNeil, 2004; Hudson et al., 1997). Rinaldi et al. (2001), for example, point out that urban infrastructures are extremely interconnected and mutually dependent in complex ways. In the other words, what happens to one of these systems may directly and indirectly affect other systems. In the same line, Chunlei et al. (2011) argue that urban infrastructure systems are not only with huge scale, but also interdependent systems. A sectional stoppage to one of urban infrastructure systems might cause a cascading failure to other ones as well as trigger huge negative impact on municipal systems. Sanford Bernhardt and McNeil (2004) state that the behavior of urban infrastructure, as such water supply system, is influenced by other systems, as such electric network, as well as affecting and constrains them. These mutual affecting natures can be traced in three main phases of UI-provision, Planning, Financing and Implementation phases. Hence, managing the interdependencies between urban infrastructure, or as Malone and Crowston (1994) called it " coordination", is a key factor in UI-provision process.

Rinaldi et al. (2001) classify the interdependencies between urban infrastructure systems into four major categories, physical, geographical, cyber, and logical. Physical interdependency means there is an input-output linkage between urban infrastructure agents. Geographical interdependency implies a status in which a restricted occurrence may result in state changes in all of urban infrastructure systems. This kind of interdependencies is a consequence of the spatial closeness of infrastructure elements. Cyber interdependency refers to a status in which informational links splice urban infrastructure to one another. If urban infrastructure being linked through human decisions, it would be posed that there is a logical interdependency between them. Furthermore, there are some other types of interdependencies among urban infrastructure systems, such as timing interdependency and financing interdependency, as discussed below, which make coordination to be an essential factor in the process of provision of them. Timing interdependency means that there is a chronological sequence in the UI-provision, as an example, designing and construction of streets, excepting pavement segments, are prior to providing other types of urban infrastructures. Financing interdependency implies a resource dependency between provision of various kinds of urban infrastructure systems. That is why, according World Bank (1994), public financing is the main resource of UI-provision worldwide.

Hence, taken together, the complex nature of urban infrastructure as well as the triple role of human beings in the UI-provision process, in one side. And considering the existence of multiple interdependencies between urban infrastructure (as of a system or organization), in other side. It can be concluded that coordination is vital mechanism through which different urban infrastructure agencies come together with the intention of making their efforts in the context of UI-provision more compatible (in terms of efficiency, effectiveness and equity). Therefore, urban infrastructure agencies (UIAs) must work in a tightly coordinated way in order to efficiently and effectively achieve goals.

6. Methodology

The adopted research methodology was relied on the use of case study method, coordination theory (Malone & Crowston, 1994), and agent-based modeling principles. The methodology contained four steps. The initial step involved an exhaustive review of the literature on coordination aspects, urban infrastructure provision, and agent-based modeling, brief portions of which are embedded in preceding segments. In the next step, based on the reviewed literature, a theoretical framework has been developed. Conducting case study, based on the theoretical framework, formed third step. Final step devoted to develop an agent-based framework aimed to improve coordination in the process of the UI-provision.

6.1. Theoretical Framework

Based on coordination theory (Malone & Crowston, 1994), the fundamental insight of the theoretical framework presented here is that coordination is the process of managing interdependencies among the activities. The framework highlights the interdependencies among urban infrastructures and corresponding urban infrastructure agencies (UIAs), which are essential for coordination in the process of UI-provision for new housing development areas. Therefore, further progress can be achievable by characterizing diverse kinds of interdependencies and recognizing the coordination mechanisms that should be applied to manage them.

Interdependency has been defined by Rinaldi et al. (2001) as a two-sided relationship between the two urban infrastructures in which the state of each urban infrastructure systems influences the state of other systems and would be influenced by them. By definition, what happens to one urban infrastructure system can directly and indirectly affect other systems as well as affect large geographic regions of the cities. This term is conceptually simple; it implies the connections among agents (organizations) in the context of provision of different urban infrastructures. But, on the other side, in practice the interdependencies among urban infrastructure radically increase the overall complexity of the "system of systems." However, the mentioned authors identified four major classes of interdependencies among urban infrastructure systems: cyber, physical, geographical, and logical interdependencies. However, there are various other interdependencies that need to be accounted in the process of urban infrastructure provision.

6.2. Findings of Case Study

Description of Cases. The processes of UI-provision for two new residential areas in Iran, namely, "Phase 7" in Hashtgerd New City and "Omid-e Ekbatan" were selected as study cases. "Phase 7" of Hashtgerd New City is one of "Mehr" scheme projects, "Mehr" scheme is a wide government housing program aimed to provide housing for low-income people in Iran. This housing project site includes 50,000 housing units. Omid-e Ekbatan is also a "Mehr" scheme project located in the north of Hamedan city. Omid-e Ekbatan comprises 2200 housing units.

Most of the data collection was done in semi-structured interview with members of the different urban infrastructure agencies (UIAs) involved in UI-provision for these tw separated new housing development areas. The interviewees have been selected according to Snowball, chain or network sampling – Strategy in which each interviewee would be selected by asking other participants. As March and Simon (1958) argued most information are stored in the minds of employees who carry out the process, or in the minds of their associates, subordinates or superiors. According to these authors, the most accurate and simplest way to discover this information is to interview them. In our cases, data was collected by asking subject questions, considering the aforementioned theoretical framework, such as: (1) what kinds of interdependencies are there between urban infrastructure agencies in the context of the UI - provision? (2) How these interdependencies constrain the effectiveness of the process of UI-provision? (3) How can these interdependencies be managed?

The second and less important source of data was documents describing the process of provision of each urban infrastructure as well as the interacting among different urban infrastructure agencies. The interpretation of these kinds of documents depends on the purpose they are intended to serve (March & Simon, 1958). However, considering the scope of the theoretical framework, following interdependencies between urban infrastructure and corresponding agencies have been identified:

Timing interdependency. This type of interdependency indicates a sequential relationship between the provision of urban infrastructure. For example, construction of street substructure is prior to the provision of other infrastructure such as water pipeline or gas pipeline. As another example, on the other hand, street pavement construction is subject to completion of construction of other infrastructures.

Input-output interdependency. If the function of one of urban infrastructures depends on the output material(s) of other one. As the name connotes there is physical linkage between the output and input of two or more urban infrastructures. For instance, the output of electricity company (electric power) is an essential input to the water company. It is worth to note that this kind of interdependency has been identified by Rinaldi et al. (2001) as "physical interdependency".

Technical info interdependency. This kind of interdependency implies a situation in which the technical information of one of infrastructure is required for proper implementation of other ones. For instance, the knowledge about the elevation of street centerline is a requisite factor proper implementation of wastewater collection system. As another example, the knowledge about the capacity of the capacity of water pipelines is a required information for designing building density.

Location interdependency. A location interdependency arises when elements of different urban infrastructure are in closed spatial proximity. Stated alternately, urban infrastructures are location interdependent if a positional event caused states changes in all of them. For instance, given this closed nearness, a physical damage to a part of a street can create state changes or correlated disturbances in other kinds of urban infrastructure which are embedded in that part of the street. To reiterate, in the words of Rinaldi et al. (2001), location interdependency, or geographic interdependency as they called it, is simply due to nearness of infrastructure elements, the state of one infrastructure does not influence the state of another.

Financial interdependency. This type of interdependency implies a situation in which there is a financing interaction between urban infrastructure agencies (UIAs) in the context of UI-provision; or financial aspects, such as resource interdependency, constrain the process of provision of infrastructure. In the both two study cases, like other part of the world (World Bank, 1994), the governmental financing resources are the major sources for UI-provision. This unique sharing resource arises financial interdependency which, in turn, constrains the process of UI-provision.

Legal interdependency. Laws and regulations governing the provision of urban infrastructures for new development areas cause legal interdependency. Legal interdependency might be linked to a government scheme that links urban infrastructure agencies (UIAs) to each others. In particular, human decisions might play a prominent role in legal interdependency. For instance, housing and urban development laws, in our case studies, connected UIAs to each others. Again, this kind of urban infrastructure interdependencies has been identified by Rinaldi et al. (2001) as *logical interdependency.* These authors believe that two urban infrastructures are logically interdependent if the state of one of them depends on the other one via a mechanism which is not cyber, physical, or geographic connection.

Administrative interdependency. The final type of urban infrastructure interdependency, which has been identified from our study cases, is administrative interdepdency between UIAs. This kind of interdependency implies a situation in which state of one infrastructure provision depends on bureaucratic process in other urban infrastructure agencies. For example, construction of water and wastewater networks is contingent upon obtaining excavation permission from municipalities. In turn, obtaining excavation permission depends on the bureaucratic process in municipalities.

7. Proposed Agent-Based Framework

ABM, as discussed above, has the capability to manage the complex interdependencies in the process of UI-provision. In this section we propose an agent-based framework to improve coordination in the context of the UI-provision. ABM frames urban infrastructure systems from the bottom up, by studying the behaviors of its constituent units, the agents. Axelrod and Tesfatsion (2006) argue that ABM is suitable paradigm for modeling when the process is consisted of interacting agents as a well as emergent phenomenon is a common characteristic of the process. Most of the UI-provision challenges, especially coordination challenges, fall into this category.

In the framework, agents behave and interact with one another as well as with their environment based on predefined formulas which are designed to imitate their corresponding entities in the real world. To wit, in a simulation environment agents interact by processing input information governed by a set of rules to produce an action. The process is then simulated, and agent behaviors (in this case, the interdependencies between UIAs) arise from interactions between agents.

The model ontology includes knowledge about the process of urban infrastructure provision and the related interdependencies. As mentioned above, these interdependencies are: timing interdependency, input-output interdependency, technical info interdependency, location interdependency, financial interdependency, legal interdependency, and administrative interdependency. Broadly, in our modeling framework, as shown in figure 1, each agent has two functional parts. One part is used for providing information about the agent's attributes: constraints, capabilities, and interdependencies. The another part is associated to interact, negotiate, with other agents. For example, agents may negotiate about the required volume of water (input-output interdependency) or about the exact location of the gas pipeline (location interdependency).

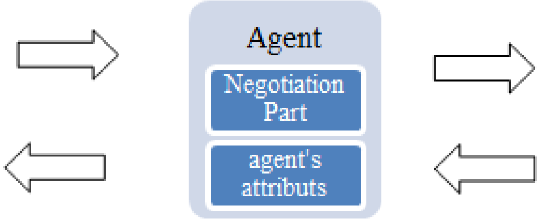

Fig. 1. An Agent

7.1. Agent Definition

In order to develop an agent-based framework, one should define the agents as well as their interactions. In our modeling framework, we define seven autonomous and semi-autonomous agents: Housing Co Agent (HCA), Road Co Agent (RCA), Water Co Agent (WCA), Sewage Co Agent (SCA), Gas Co Agent (GCA), Electricity Co Agent (ECA), and Telecommunication Co Agent (TCA).

Housing Co Agent (HCA) plays a central role in the proposed framework. HCA represents government agency who is responsible for planning and providing social housing for the low-income community. Agent's attribute: one of the model's fundamental assumptions is that other agents are expected to serve this agent according to its expectation.

Road Co Agent (RCA) represents real world agency who is in charge of designing and construction of the street. Agent's attribute: since other urban infrastructures are usually embedded in the streets, there are significant interdependencies between streets and other types of urban infrastructures. For this reason, RCA takes a salient role in our model.

Water Co Agent (WCA) is defined to represent the government organization, or part of an organization, who is involved in designing water network and providing potable water for a new residential area. Agent's attribute: this agent in the context of providing services has some technical and financial limitations such as water pressure, pipeline capacity, distance between water sources and users, etc. These limitations, in turn, trigger some interdependencies between agents.

Sewage Co Agent (SCA) represents government organization, or part of an organization, who is responsible for designing sewage network and collection of wastewater. Agent's attribute: in the context of providing services, SCA encounters with some constraints. Its technical constraints can be enumerated as: land slope gradient, soil type, mean land elevation, and so on. Also financing constraints influence the ability of this agent. However, in turn, these constraints arouse some sort of interdependencies.

Gas Co Agent (GCA), in the proposed framework, delegates governmental organization who is involved in designing and providing natural gas infrastructure for new residential areas. Agent's attribute: like other agents, GSA has its own constraints in the context of service provision for new housing development areas. These limitations are: Capacity of pipelines, capacity of city gate stations (C.G.S) and Town Border Station (T.B.S), financing constraint, etc.

Electricity Co Agent (ECA), in our modeling framework, deputizes government agency involved in designing and providing electricity power for new residential areas. Agent's attribute: in the context of service provision for new residential areas this agent, like other agents, has some technical and financial limitations such as wiring capacity, power plant capacity, distance between power station and users, etc.

Telecommunication Co Agent (TCA), in the modeling framework, represents government agency who is involved in designing and providing telecommunication services for new residential areas. Agent's attribute: TCA, like other agents, in the context of service provision for new housing areas, has some constraints. These technical and financial constraints are: distribution density planning, telecommunication equipment capacity, distance between Telecommunication installations and users, etc.

7.2. Agent Interactions

As mentioned in previous sections, the ultimate goal of our modeling approach is to build up an agent-based framework in order to coordinate different urban infrastructure agencies (UIAs) in the context of UI-provision for a new residential area. Based on coordination theory (Malone & Crowston, 1994), coordination is managing interdependencies between activities. To this end, in the framework, predefined agents interact (negotiate) in order to manage the interdependencies such as timing interdependency, input-output interdependency, technical info interdependency, location interdependency, financial interdependency, legal interdependency, and administrative interdependency.

As shown in fig. 2, using Agent Communication Language (ACL), ACL is a language with precisely defined semantics, syntax, and pragmatics that is the basis of communication between independent agents, agents intact, negotiate, with each other in order to manage their interdependencies. Since in our modeling framework every two agents negotiate directly, pair-wise negotiation protocol, in which one agent sends an "ask" and the other agent send a "reply", would be applied. However, the overall negotiation process would be done in two main stages; selecting a suitable residential sit (in term of providing urban infrastructure), and providing urban infrastructure for the designated site.

In the first stage, site selection stage, input-output interdependency, legal interdependency, and financial interdependency through a negotiation process would be managed. Initially, HCA starts negotiation by sending calling for proposals (CFP) message, including sites' features and projected number of residential units, to other agents. Message-recipient agents, after comparing the CFP with their own attributes (capabilities and constraints), reply to HCA. After several rounds of conversation, in which proposes and counter-propose are exchanged, the negotiation between HCA and other agents would be ended when all agents reach (do not reach) to an agreement on the location of residential site and the number of residential units. It is evident that input-output, legal and financial interdependency directly affect the negotiation process. In the other words, the results of interactions between agents would be based on these interdependencies.

Second stage, providing urban infrastructure, comprises two sub-stages; designing urban infrastructure networks and construction of urban infrastructure elements. In the former sub-stage, technical info interdependency would be managed. In the later one, construction stage, timing interdependency, location interdependency, financial interdependency, and administrative interdependency would be managed. The process of interactions, negotiations, among agents in this stage is similar to the first stage.

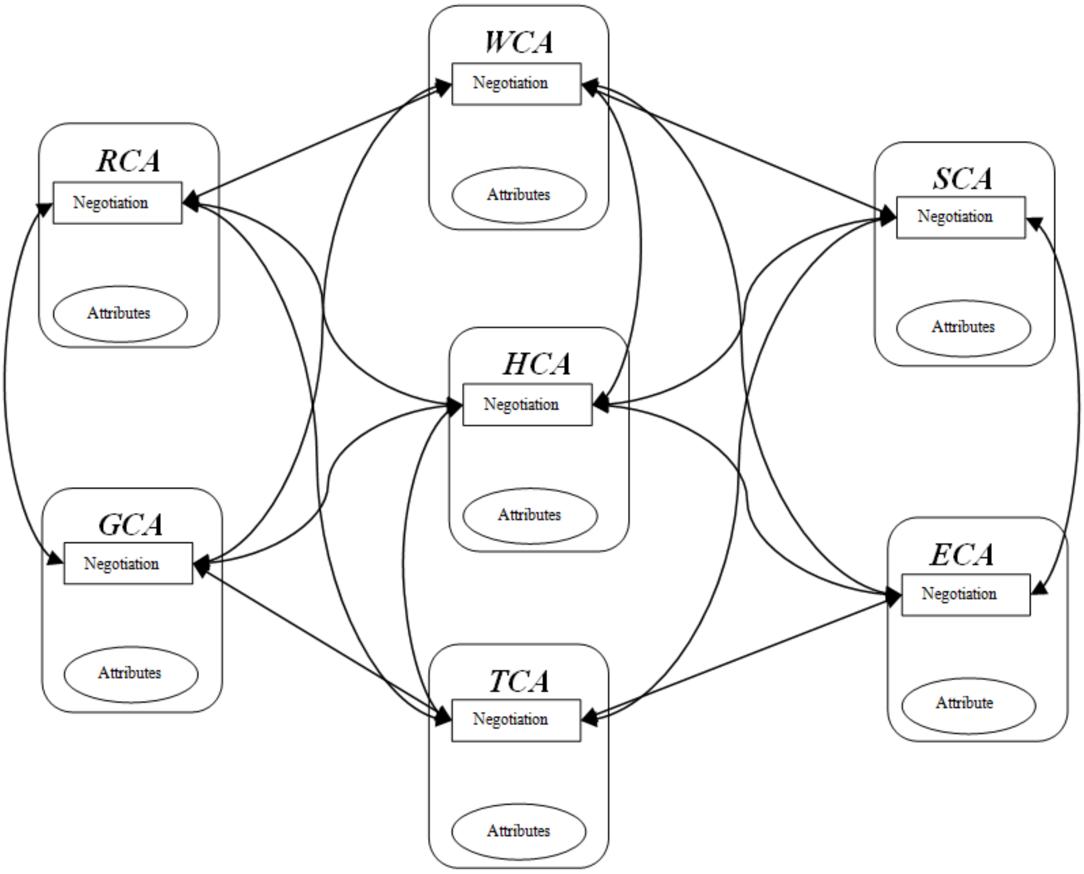

Fig. 2. Agent Interactions

8. Conclusions

Involvement of different independent agencies in the process of urban infrastructure requires a great amount of coordination between them. That is, coordination brings together these agencies to make their endeavors more compatible in the favor of efficiency and effectiveness. This paper by identifying various kinds of interdependencies in the context of urban infrastructure provision provides a ground for decision-maker to consider the potentials and limitations of urban infrastructures when they plan for a new development area. Moreover, by hybridization of two domains of science, namely, coordination science and complex system science, and based on empirical data (resulted from two case studies in Iran), we developed an agent-based coordination framework. The framework, offers a logical mindset to manage various interdependencies between different agencies involved in the process of urban infrastructure provision in Iran. In the proposed framework, agents, which represent government agencies involved in the UI-provision, based on a set of predefined interaction roles negotiate with one another to coordinate their activities. The approach demonstrated here is generic and can be applied to support the decision making process in the urban–related topics.

References

[1] Amin, M. (2002a). “Toward secure and resilient interdependent infrastructures.” J. Infrastruct. Syst., 8(3), 67–75.

[2] Amin, M. (2002b). “Modelling and Control of Complex Interactive Networks", *IEEE Control System Magazine*, pp. 22-27, 2002.

[3] Axelrod, R. & Tesfatsion, L. (2010). On-Line Guide for Newcomers to Agent-Based Modeling in the Social Sciences. from /http: // www2.econ.iastate.edu/tesfatsi/abmread.htmS.

[4] Axelrod, R.(1997).The Complexity of Cooperation: Agent-Based Models of Competition and Collaboration. Princeton University Press, Princeton, NJ.

[5] Axelrod, R. & Tesfatsion, L. (2006). A guide for newcomers to agent based modeling in the social sciences.Handbook of computational economics. Vol. 2: Agent-based computational economics, L. Tesfatsion and K. L. Judd, eds., Handbooks in Economics Series, Elsevier/ North-Holland, Amsterdam, The Netherlands.

[6] Bak, P. (1996) How Nature Works: The Science of Self-Organized Criticality, Springer-Verlag, New York, NY.

[7] Barabasi, A.L. (2002). Linked: The new science of networks. New York: Perseus.

[8] Bar-Yam, Y. (1997). Dynamics of complex systems (Vol. 213). Reading, MA: Addison-Wesley.

[9] Batty, M. (2005). Cities and Complexity: Understanding Cities with Cellular Automata, Agent-Based Models, and Fractals. Mass.: MIT Press, Cambridge.

[10] Baynes, T. M. (2009). Complexity in urban development and management.Journal of Industrial Ecology, 13(2), 214-227.

[11] Benenson, I. (1999). Modelling population dynamics in the city: from a regional to a multi-agent approach. Discrete Dynamics in Nature and Society 3, 149–170.

[12] Berger, T. (2001). Agent-based spatial models applied to agriculture: a simulation tool for technology diffusion, resource use changes, and policy analysis. Agricultural Economics 25, 245–260.

[13] Bonabeau, E. (2002). Agent-based modeling: Methods and techniques for simulating human systems. Proceedings of the National Academy of Sciences 99 (3), 7280–7287.

[14] Brown, D., Riolo, R.L., Robinson, D.T., North, M., & Rand, W. (2005). Spatial process and data models: toward integration of agent-based models and GIS. Journal of Geographical Systems7 (1), 25–47.

[15] Brown, D. & Xie, Y. (2006). Spatial agent-based modeling. International Journal of Geographical Information Science 20 (9), 941–943.

[16] Buchanan, M. (2009). Economics: Meltdown modelling. Nature 460 (7256), 680–682.

[17] Castelfranchi, C. (1995). Guarantees for autonomy in cognitive agent architecture. In: Wooldridge, M.J., Jennings, N.R. (Eds.), Intelligent Agents: Theories, Architectures, and Lan- guages (LNAI Volume 890). Springer-Verlag, pp. 56–70.

[18] Chen, L. (2012). Agent-based modeling in urban and architectural research: A brief literature review.Frontiers of Architectural Research,1(2),166-177.

[19] Chunlei, W., Lan, F., & Yiqi, D. (2011). National Critical Infrastructure Modeling and Analysis Based on Complex System Theory. In Instrumentation, Measurement, Computer, Communication and Control, 2011 First International Conference on (pp. 832-836). IEEE.

[20] Cirillo, R., Thimmapuram, P., Veselka, T., Koritarov, V., Conzelmann, G., Macal, C., ... & Cheng, X. (2006). Evaluating the potential impact of transmission constraints on the operation of a competitive electricity market in Illinois. Report ANL, 16(06).

[21] Davis, D.N. (2000). Agent-based decision-support framework for water supply infrastructure rehabilitation and development, Computers, Environment and Urban Systems 24 (2000) 173–190.

[22] de la Garza, J.M., Drew, D.R., & Chasey, A.D. (1998). Simulating Highway Infrastructure Management Polices. Journal of Engineering Management, 13(5), 64-72.

[23] Dennet, D. (1996). Darwin's Dangerous Idea: Evolution and the Meanings of Life. Simon & Schuster.

[24] De Smith, M.J., Goodchild, M.F., & Longley, P.A., (2007). Geospatial Analysis: A Comprehensive Guide to Principles, Techniques and Software Tools, second ed. Leicester, Matador.

[25] Drogoul, A. & Ferber, J. (1994). Multi-Agent Simulation as A Tool for Studying Emergent Processes in Societies. In: Gilbert, N., Doran, J. (Eds.), Simulating Societies: The Computer Simulation of Social Phenomena. University College London Press, London.

[26] Engel-Yan, J., Kennedy, C., Saiz, S., & Pressnail, K. (2005). Towards Sustainable Neighbourhoods: The Need to Consider Infrastructure Interactions, available at:www.nrca.org.

[27] Epstein, J.M. & Axtell, R. (1996). Growing Artificial Societies: Social Science from the Bottom up. Brookings Institution Press, Washington, D.C.

[28] Feldman, R.D., Mudge, R., & Rubin, K.I. (1988). Financing Infrastructure Tools for the Future. New York: Executive Enterpris es, Inc.

[29] Feuillette, S., Bousquet, F., & Le Goulven, P. (2003). SINUSE: a multiagent model to negotiate water demand management on a free access water table. Environmental Modelling and Software 18,413–427.

[30] Fischer, K., Muller, J.P., & Pischel, M. (1996). Cooperative transportation scheduling: An application domain for DAI. Applied Artificial Intelligence 10 (1), 1–34.

[31] Gall, J. (2002). The Systems Bible: The Beginner's Guide to Systems Large and Small: Being the Third Edition of Systemantics. General Systemantics Press.

[32] Gilbert, N. & Terna, P. (2000). How to build and use agent-based models in social science. Mind and Society 1 (1), 57–72.

[33] Gilbert, N. (2008). Agent-Based Models. Sage Publications, Los Angeles.

[34] Grimm, V., Berger, U., Bastiansen, F., Eliassen, S., Ginot, V., Giske, J., ... & DeAngelis, D. L. (2006). A standard protocol for describing individual-based and agent-based models. Ecological modelling, 198 (1), 115-126.

[35] Haimes, Y.Y. & Jiang, P. (2001). Leontief-Based Model of Risk in Complex Interconnected Infrastructures. ASCE Journal of Infrastructure Systems, 7(1), 1-12.

[36] Hayes, C.C. (1999). Agents in a nutshell -a very brief introduction. IEEE Transactions on Knowledge and Data Engineering 11 (1), 127–132.

[37] Hejazi, S. J. (2003). Quality urban regeneration, co-ordinated professional leadership and integrated urban management in western Europe: Learning from Europeanexperience in relation to the Iranian context. Newcastle upon Tyne: Newcastle University.

[38] Heller, M. (2002, September). Interdependencies in civil infrastructure systems. In Frontiers of Engineering: Reports on Leading-Edge Engineering from the 2001 NAE Symposium on Frontiers of Engineering (p. 47). National Academies Press.

[39] Hoffmann, M., Kelley, H., Evans, T., & Janssen, M. A. (2002). Simulating land-cover change in South-Central Indiana: an agent-based model of deforestation and afforestation. Complexity and ecosystem management: The theory and practice of multi-agent systems, 218-247.

[40] Hogeweg, P. & Hesper, B. (1983). The ontogeny of the interaction structure in BumbleBee colonies: a MIRROR model. Behavioral Ecology and Sociobiology 12, 271–283.

[41] Holland, J. H. (1995). Hidden Order: How Adaptation Builds Complexity. Addison-Wesley: Reading, MA.

[42] Holland, J. H. (1988). "The global economy as an adaptive process." The economy as a an evolving complex system, P.W. Anderson, K. J. Arrow, and D. Pines eds., Addison–Wesley, Redwood City, Calif.

[43] Hudson, R., Haas, R., & Uddin, W. (1997). Infrastructure Management: Integrating Design, Construction, Maintenance, Rehabilitation, and Renovation. McGraw Hill, New York, NY.

[44] Jacobs, J. (1961). The death and life of great American cities. New York: Vintage/Random House.

[45] Jennings, N.R., Sycara, K. & Wooldridge, M. (1998). A roadmap of agent research and development. Autonomous Agents and Multi- Agent Systems 1, 7–38.

[46] Jiang, B. & Gimblett, H.R. (2002). An Agent-Based Approach to Environmental and Urban Systems within Geographic Information Systems. In: Gimblett, H.R. (Ed.), Integrating Geographic Information Systems and Agent-Based Modeling Techniques for Simulating Social and Ecological Processes. Oxford University Press, Oxford, pp. 171–190.

[47] Jiang, T. & Tianfield, H. (2006). "Literature Review Upon Multi-Agent Supply Chain Management," Machine Learning and Cybernetics, 2006 International Conference on, vol., no., pp.89,94. doi: 10.1109/ICMLC.2006.258877.

[48] Khan, M. M. (1997). Urban Local Governance in Bangladesh: An overview. In N. Islam & M. M. Khan (Eds.), Urban governance in Bangladesh and Pakistan (pp. 7–26). Dhaka: Centre for Urban Studies.

[49] Kikuchi, S., Rhee, J., & Teodorovic, D. (2002). Applicability of an agent-based modeling concept to modeling of transportation phenomena. Yugoslav Journal of Operations Research ISSN: 0354-0243 EISSN: 2334-6043, 12(2).

[50] Kii, M. & Doi, K. (2005). Multiagent land-use and transport model for the policy evaluation of a compact city. Environment and Planning B: Planning and Design 32, 485–504.

[51] Kjenstad, D. (1998). Coordinated supply chain scheduling. Ph.D. Thesis. Department of Production and Quality Engineering, Norwegian University of Science and Technology.

[52] Kohler, T.A. & Gumerman, G. (2001). Dynamics in Human and Primate Societies.Oxford University Press,New York.

[53] Langton, C.G. (1989). Artificial life. In: Langton CG (ed). Artificial Life: The Proceedings of an Interdisciplinary Workshop on the Synthesis and Simulation of Living Systems (held September 1987, Los Alamos, New Mexico, Vol. VI in Santa Fe Institute Studies in the Sciences of Complexity), Addison-Wesley: Reading, MA, pp 1–47.

[54] Lansing, J.S. & Kremer, J.N. (1993). Emergent properties of Balinese water temple networks: coadaptation on a rugged fitness land- scape. American Anthropologist 95 (1), 97–114.

[55] Levinson, D. & Yerra, B. (2006). Self-organization of surface transportation networks. Transp. Sci., 40_2_, 179–188.

[56] Little, R. G. (2002). "Controlling cascading failure: Understanding the vulnerabilities of interconnected infrastructures." J. of Urban Technology, 9(1), 109–123.

[57] Liu, Z. (2004). Planning and Policy Coordination in China's Infrastructure Development. Background paper commissioned for the ADB-JBIC-World Bank East Asia and Pacific Infrastructure Flagship Study.

[58] Luck, M., McBurney, P., & Preist, C. (2003). Agent Technology: Enabling Next Generation Computing: A Roadmap for Agent Based Computing. AgentLink II.

[59] Macal, C.M. & North, M.J. (2006). Tutorial on agent-based modeling and simulation part 2: how to model with gents. In Proceedings of the 38th conference on Winter simulation (WSC '06), L. Felipe Perrone, Barry G. Lawson, Jason Liu, and Frederick P. Wieland (Eds.). Winter Simulation Conference 73-83.

[60] Macal, C. M. & North, M. J. (2008, December). Agent-based modeling and simulation: ABMS examples. N Proceedings of the 40th Conference on Winter Simulation (pp. 101-112). Winter Simulation Conference.

[61] Macal, C.M. & North, M.J. (2010). Tutorial on agent-based modelling and simulation. Journal of Simulation. 4, 151–162.

[62] Malone, T.V. & Crowston, K. (1994). The Interdisciplinary Study of Coordination. ACM Computing Surveys, Vol. 26, No. 1, March 1994.

[63] March, J. G., & Simon, H. A. (1958). Organizations. New York: John Wiley.

[64] Miller, J. H. & Page, S. E. (2007). Complex adaptive systems: An introduction to computational models of social life. Princeton, NJ: Princeton University Press.

[65] Minar, N., Burkhart, R., Langton, C. & Askenazi, M. (1996). The Swarm simulation system, a toolkit for building multi-agent simulations, retrieved from <http://www.santafe.edu/projects/swarm/overview/overview.html>.

[66] Mintzberg, H. (1993). Structure in Fives. Designing Effective Organizations, Prentice-Hall, Englewood Cliffs, USA.

[67] Mitchell, M., & Newman, M. (2002). Complex systems theory and evolution. Encyclopedia of Evolution, 1-5.

[68] Nagel, K. & Rasmussen, S. (1994). Traffic at the edge of chaos. In: Brooks, R.A., Maes,P.(Eds.), Artificial Life IV: Proceedings of the Fourth International Workshop on the Synthesis and Simulation of Living Systems. MIT Press, Cambridge, MA, pp. 222–235.

[69] NetLogo (2006). NetLogo home page. <http://ccl.northwestern.edu/netlogo>.

[70] Nikolic, I. & Dijkema, G. P. J. (2010). On the development of agent-based models for infrastructure evolution. IJCIS, 6, 148-167.

[71] North, M. J., Collier, N. T. & Vos, J. R. (2006). Experiences in Creating Three Implementations of the Repast Agent Modeling Toolkit, ACM Transactions on Modeling and Computer Simulation, 16(1):1-25, January.

[72] North, M. J. & Macal, C. M. (2005). Escaping the accidents of history: an overview of artificial life modeling with Repast. In *Artificial Life Models in Software*, eds. A. Adamatzky and M. Komosinski, Springer-Verlag: Dordrecht, Netherlands.

[73] Osman, H. (2012). Agent-based simulation of urban infrastructure asset management activities. Automation in Construction 28 (2012) 45–57.

[74] Otegbulu, A., & Adewunmi, Y. (2009). Evaluating the sustainability of urban housing development in Nigeria through innovative infrastructure management. International Journal of Housing Markets and Analysis, 2 (4), 334–346. doi:10.1108/17538270910992782.

[75] Panday, P.K. & Jamil, I. (2010). Challenges of Coordination in Implementing Urban Policy: The Bangladesh Experience. Public Organiz Rev (2011) 11:155–176.

[76] Panzieri, S., Setola, R., & Ulivi, G. (2004, October). An agent based simulator for critical interdependent infrastructures. In Proceedings of the 2nd International Conference on Critical Infrastructures (pp. 24-27).

[77] Parker, D.C. & Meretsky, V. (2004). Measuring pattern outcomes in an agent-based model of edge effect externalities using spatial metrics. Agriculture Ecosystems and Environment 101, 233–250.

[78] Porter, D.R. (Ed.) (1986). Growth Management. The Urban Land Institute.

[79] Reynolds, C.W. (1987). Flocks, herds, and schools: a distributed behavioral model. Computer Graphics 21 (4), 25–34.

[80] Rindfuss, R., Entwistle, B., Walsh,S.J., An, L., Brown, D.G., Deadman, P.,et al.,(2008).Land use change: Complexity and comparisons. Journal of Land Use Science 3 (1), 1–10.

[81] Rinaldi, S., Peerenboom, J., and Kelly, T. (2001). Identifying, Understanding and Analyzing Critical Infrastructure Interdependencies, IEEE Control Systems Magazine, December, 11-25.

[82] Sanford, M. & Newman, M. (2002) “Complex Systems Theory and Evolution," In Encyclopedia of Evolution, ed. Pagel, M. (Oxford University Press).

[83] Sanford Bernhardt, K. L. (2004). “An agent-based framework for modeling civil infrastructure systems management.” Proc., Information Technology in Civil Engineering Symp., ASCE, Baltimore.

[84] Sanford Bernhardt, K. L., & McNeil, S. (2004). An agent-based approach to modeling the behavior of civil infrastructure systems. In Presentation at Engineering Systems Symposium. MIT.

[85] Sanford Bernhardt, K. L., & McNeil, S. (2008). Agent-Based Modeling: Approach for Improving Infrastructure Management. Journal Of Infrastructure Systems, 14:253-261.

[86] Sakoda, J.M. (1971). The checkerboard model of social interaction. J Math Sociol 1: 119–132.

[87] Saunders, R., & Gero, J. S. (2004). Curious agents and situated design evaluations.AI EDAM,18 (2), 153-161.

[88] Schelling T.C. (1978). Micromotives and Macrobehavior. Norton: New York.

[89] Stead, D. (2008). Institutional aspects of integrating transport, environment and health policies, Transport Policy, 15, pp. 139–148.

[90] Siddique, K. (Ed.). (1994) Local government in Bangladesh.Dhaka: University Press Limited.

[91] Sohail, M., Asce, M., Cavill, S., & Cotton, A. P. (2005). Sustainable Operation and Maintenance of Urban Infrastructure: Myth or Reality?, (March), 39–49.

[92] Sözüer, M. & Spang, K. (2012). Challenges in the Planning Process of Infrastructure Projects in Germany. Construction Research Congress 2012: pp. 2369-2378. doi:10.1061/9780784412329.238.

[93] Tian, J. & Tianfield, H. (2006). "Literature Review Upon Multi-Agent Supply Chain Management," Machine Learning and Cybernetics, 2006 International Conference on, vol., no., pp.89, 94, 13-16. doi: 10.1109/ICMLC.2006.258877.

[94] Tillman, D., Larsen, D., Pahl-Wostl, C., & Gujer, W. (1999). Modeling the actors in water supply systems, Water Science and Technology 39, 203–211.

[95] Tornberg, P. (2012). Committed to Coordination?: how different forms of commitment complicate the coordination of national and urban planning. Planning Theory & Practice, 13(1), 27-45.

[96] Weisbuch, G. (1991). Complex Systems Dynamics: An Introduction to Automata Networks (translated from French by S. Ryckebusch), Addison-Wesley: Redwood City, CA.

[97] Wolfram, S. (2002). A New Kind of Science. Wolfram Media, Inc, Champaign, IL.

[98] Wooldridge, M. (2002). Introduction to MultiAgent Systems, Wiley.

[99] Wooldridge, M. & Jennings, N.R. (1995). Intelligent agents: theory and practice, Knowledge Engineering Review, 10 (2), pp. 115-152.

[100] World Bank (1994). WDR 1994: Infrastructure for Development. World Bank and Oxford University Press. ISBN: 978-0-19-520992-1, DOI: 10.1596/978-0-19-520992-1.

[101] Wu, W. (1999). Reforming China’s institutional environment for urban infrastructure provision. Urban Studies, Vol. 36, 2263–2282.

[102] Yerra, B. M. & Levinson, D. M. (2005). The emergence of hierarchy in transportation networks. Ann. Reg. Sci., 39_3_, 541–553.

[103] Yazdani, S., Dola, K., Azizi, M. M., & Yusof, J. M. (2015). Challenges of Coordination in Provision of Urban Infrastructure for New Residential Areas: The Iranian Experience. Environmental Management and Sustainable Development, 4(1), 48-72.

[104] Zechman, E. (2011). Agent-based modeling to simulate contamination events and evaluate threat management strategies in water distribution systems, Risk Analysis 31 (2011) 758–772.