Article

Complexity and Dynamics in Construction Project Organizations

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Abstract: Despite the significant influence of organizational elements on the performance of construction projects, these elements are regarded as fixed, or reflected in an implicit manner, in current project management techniques. This study investigated how the organizational dynamics formed within a project organization based on complexity theory are described, and how organizational factors affect project performance during a construction project. It also presented agent-based simulation (ABS) as a means to understand organizational dynamics in construction project organizations. The author found that manager optimism bias toward organizational factors leads to unrealistic project planning and execution, ultimately having negative effects on project performance, and that developing ABS could enhance the understanding of the organizational aspect in the construction management process. This study is significant, as it enhances the understanding of the organizational aspect of a construction project, and presents a new direction for reflecting the organizational aspect in the project management process.

Keywords: construction project organization; construction management; project performance; complex system; agent-based simulation

1. Introduction

1.1. Background and Objectives of the Research

The successful implementation of a construction project is highly dependent on technical and managerial aspects, as well as the organizational aspect [1]. Smooth information sharing and communication among members of the project organization in the pre-construction stage lead to the production of project-related information, such as drawings and specifications, with fewer defects. Moreover, close cooperation in the project execution stage becomes an important factor for enhancing the productivity of work and determining overall performance [2].

This organizational importance arises from the temporary nature of the construction project organization, in contrast with other manufacturing industries. In this respect, the participants in this one-off construction project form a temporary organization for that purpose [3]. Temporary organizations, unlike permanent organizations, undergo a continuous redesign process throughout an entire implementation stage, due to lack of common understanding and the organizational structure of members [4]. Thus, organizational failures can lead to negative results, such as construction delay and project cost overrun [3].

There is a growing organizational importance of the successful implementation of a project with a scale-up and convolution of construction projects, as well as the increasing introduction of collaborative project implementation techniques [5]. A complex large-scale project requires thorough planning and execution, based on expertise and data from various fields, as well as project execution experience. Even an experienced expert or organization cannot meet all needs in a complex project, necessitating cooperative efforts for efficient work performance and problem solving among various participants. Furthermore, over the years, there has been a growing application of collaborative project implementation techniques among construction project organizations, such as Construction...
Management at Risk (CMAR), Integrated Project Delivery (IPD), and Off-Site Construction (OSC), highlighting the importance of the organizational aspect.

Despite the significant influence of organizational elements on the performance of construction projects, these elements are regarded as fixed, or reflected in an implicit manner, in current project management techniques [6]. The critical path method (CPM), which is a typical project management technique, does not consider the effects of information dependence and interactions among project participants, which are mostly reflected to a greater or lesser extent depending on the experience or judgment of a manager regarding various project situations.

Recent studies on complex systems have attempted to understand the nature of an organization from a social and organic viewpoint, rather than a simple mechanical one, as hierarchical entanglement [7]. A complex system refers to a system in which the interactions among components with various characteristics result in a systemic phenomenon completely different from the characteristics of these components [8]. Under the organic view of organizations, an organization is understood on the basis of systemic characteristics that appear through interactions such as information exchange and communication among members through various networks, rather than the characteristics of individual members. The complexity perspective will provide a dynamic understanding of organizational factors that are not properly reflected in project management, as well as practical considerations.

This study seeks to determine how organizational factors affect project performance in proceeding with a construction project, and to present a method for understanding the formation of a collaborative network within the construction project organization. For this purpose, this study describes the organizational dynamics formed within a project organization based on complexity theory, a new perspective on project organization, and utilizes the agent-based modeling and simulation method, which is a representative method to explore the complexity system, in order to present a method of modeling and analyzing a project organization.

1.2. Scope and Method of Research

This study discusses the formation of a collaborative network among members in a project organization during the construction project implementation process. Despite varied information sharing and collaboration methods among members, depending on the ordering method and organizational structure of a construction project, this study assumes a general situation in which all members participate in project-related information creation from the pre-construction stage. Within this situation, we conduct a literature review to determine how organizational factors have been reflected in the project planning and implementation process in conventional construction projects. In addition, based on the complex system perspective, we describe the formation of organizational dynamics within the construction project organization. This study introduces the theory and development process of agent-based simulation (ABS), and analyzes how a collaborative network is formed within the organization by utilizing the construction project organization simulation model developed accordingly (Figure 1).

Figure 1. Research flow.
2. Literature Review

There has been research on project organization in the field of construction in various aspects. Previous studies have been conducted mainly on predicting performance from the perspective of corporate management [9,10], or establishing strategies to improve the performance [11,12]. From a strategic aspect, many studies have examined how to develop and expand businesses through partnership with other companies [13–16]. Moreover, other studies are involved in innovation through network building within the organization of a construction company [17,18], leadership [19], organizational culture [20], and learning organization [21–24].

Recent studies regarding organizations in the construction field have diversified in both scope and method. The research on the performance of the construction project organization mainly focused on the factors that determine performance. Tripathi and Jha [25] derived the success factors of a construction project organization by utilizing structural equation modeling. The same study performed a modeling based on the survey results from 106 experts, revealing that organizational factors determine the performance of the project. Hu, et al. [26] attempted to identify principal program organization factors that affect the success of organizations performing a megaproject. The same study conducted a literature review, expert interviews, and Delphi survey, and on that basis presented the following twelve program organizational factors: contextual understanding, strategy, leadership, scope management, program governance, matrix organizational structure, program management office, use of project breakdown structure, partnering, technology management, communication management, and team building. In a follow-up study, Hu, et al. [27] developed an index that can measure the performance of organizations performing megaprojects. Kwofie, et al. [28] analyzed the factors that affect the effectiveness of the construction project organization by using statistical methods. The authors conducted a multiple regression analysis on results from a survey of 98 experts, on that basis deriving the following important factors: efficient team leadership, effective communication, mutual trust among team members, well-defined team responsibilities and roles, and sound relationships among team members.

In addition to research on the performance of construction project organizations, there have been various studies regarding innovation performance indicators of organizations [29], case analyses of cooperative innovation among organizations for sustainable construction [30], knowledge sharing [31], team integration [32], and relational characteristics [33]. Notably, many studies on construction project organizations embrace the network viewpoint. Prior to the emergence of network analysis techniques, theoretical studies on networks within construction project organizations [34,35] and basic data analysis studies [36,37] were predominant. Over the recent years, studies, along with the development of network analysis, have extended to an analysis of the collaborative relationships among construction companies [38], the development of an information transmission model within the project organization [39], an analysis of the structure of the project organization [40], and collaborative innovation processes [41].

These existing studies on project organizations have dealt with the organization as a static entity or as something viewed from a strategic viewpoint at the macro level. Complex system perspective is thought to be able to present alternatives to the limitations of this existing approach. A complex system is one where a behavior of a system arises from interactions among subsystems and the emergent properties of the system are greater than the simple sum of its subsystems [42]. Complexity arises when the dependencies among the systems’ elements become important [8]. Among complex systems, those composed of interacting thoughtful agents are called complex adaptive systems (CASs) or complex adaptive social systems. CASs have common characteristics such as aggregation, nonlinearity, flow, and diversity, and often feature the system property of robustness [43]. It is believed that the global behavior of CAS emerges from the local activities of lower-level components. The global behavior of CAS is very different from those of its components, and it cannot be reduced to the sum of their differences [44]. It provides a very powerful
organizing force that can overcome a variety of changes to the lower-level components, which is called emergence [8]. These unique characteristics of CAS often make them hard to examine and difficult to understand.

The organic organization perspective can be thought of as viewing organizations under unexpected and dynamic conditions as complex systems, in the sense that it highlights local interactions among members, network characteristics, and emergent properties of organizations. Considering that organizational development and organizational knowledge creation is accomplished through continuous dialogue among individuals, teams, and levels [45], this view is valid.

Research on the organization from the perspective of a complex system has spanned several fields. Gómez-Cruz, et al. [46] conducted a literature review to analyze the tendency to utilize the ABS method in organizational behavior. The analysis of the research literature of the past seven years using the Scopus database showed that the ABS method is widely used in the fields of organizational behavior, strategy, human resources, marketing, and logistics. Haki, et al. [47] implemented the evolving process of information system architecture within an organization by using the ABS method. The authors described the process of institutional pressure affecting decisions related to the information system architecture within an organization, by implementing a theory-informed simulation model. Sharpanskykh and Haest [48] implemented the ABS method to verify the efficacy of external regulation of the employees’ behavior, and internal motivation was presented as a method to prevent ground safety occurrences. The simulation model was implemented based on the theories of social sciences, considering cognitive, social, and organizational aspects, and was able to reproduce the behavioral patterns related to the compliance of the employees in platform companies. Sokolowski, et al. [49] implemented an ABS to understand the emergence process of insider threats that may occur inside a company. They categorized the factors affecting the behavior of company employees into affective, rational, and social behaviors, and set the main motive of their behavior as the level of disgruntlement to implement a simulation. Somarathna [50] established the human resource management (HRM) process of a company as a complex system consisting of relationships among multiple autonomous human agents to develop an ABS to understand the HRM process. The authors pointed out the limitations of the conventional HRM method, which relied on analytical methods, and developed a model for analyzing the effects of alternate recruitment strategies, depending on workforce fluctuations, demographics, skill profile, loyalty, and costs. Sanchez-Cartas [51] developed an ABS model to understand the competition between companies, which affects the determination of prices in the market. The authors described the process of competition between companies based on the complex system theory, and implemented a simulation model based on game theory.

Computer simulation provides an effective approach to study a project organization from the complex system perspective. Computer simulations have been widely used in the construction management field. Discrete event simulation was mainly used to analyze the efficiency of the production process at the work level, and software dedicated to the construction field such as CYCLONE [52] and STROBOSCOPE [53] has been developed. Over recent years, system dynamics and ABS have been utilized to analyze complex and dynamic phenomena [54,55], which are evolving in connection with building information modeling (BIM) and sensing technology [56].

Recent studies have begun to employ computer simulations in investigating construction project organizations from an organic viewpoint. The development of symbolic programming, network analysis, and cognitive science has enabled an organization to be modeled in a virtual space; this has been utilized to develop and test organization theories. The prevailing ABS method is a new technique that can effectively and systematically investigate organizations from a ground-up perspective, and is actively used in fields such as sociology and economics [57]. Jin and Levitt [58] began applying computer simulations to explore construction project organizations. Their study examined the demand for cooperation arising from the interrelationship of works, by implementing a virtual
organization via computer simulation, and, based on this result, sought to determine the
effect of organizational structure on performance. Slavina, et al. [59] and Sagar, et al. [60]
continued the investigation of these construction projects, using virtual organization. There
has been research that intended to explore the construction project organization from the
perspective of the aforementioned complex system. Zhang, et al. [61] assumed that the
safety behavior of workers on the construction site was due to the interaction between
the worker’s behavior and managerial guidelines, and described the behavior by imple-
menting an ABS model. Pires and Vieira [62] argued that a construction project should be
understood from the viewpoint of a complex system, and that an ABS-based approach is
suitable. Gao, et al. [63] utilized an ABS technique to describe the process of information
sharing over a network within a construction project organization. However, most existing
studies are often based on simple assumptions or developed for special purposes, so there
is a limit to studying the dynamics of project organizations.

3. Organizational Dynamics in Construction Projects

3.1. Project Organization as Temporary Organization

The construction project organization has its own purpose, composition, and working
method, due to the characteristics of the construction industry (Table 1). The purpose of a
construction project, unlike a general manufacturing one, is determined by the client, who
is not involved in the actual implementation, and the organization is structured by factors
such as design and price, rather than the overall efficiency of the project, whose work is
typically shaped by the contractual relationship between the participants. The uniqueness
of this construction project organization arises from the nature of construction projects,
which cannot be done repeatedly. A client builds up a project organization by selecting a
designer, engineering companies, and a constructor to perform a project within different
environments (site, location) and business conditions (client, use, scale, period, budget).

As a result, a construction project organization has the character of a temporary
organization [3]. A temporary organization, contrasted with a permanent organization
within a general company, lacks a common understanding of work, an organizational
structure established for the work system, an established working method, and a cost
system for profitability calculation [64]. A construction project organization consists of
people drafted in from different companies to undertake a single project. The members,
who have to perform tasks with dynamic and relational characteristics in a construction
project organization, have to undergo a continuous re-engineering process to exchange
information necessary for work or to perform interrelated tasks [4].

| Purpose | Construction Project Organization | Manufacturing Organization |
|---------|----------------------------------|---------------------------|
| Decided by the client, rather than the entity that actually executes the business. | Decided by the manufacturer based on sufficient experience in design, production, and marketing. |

| Composition | Construction Project Organization | Manufacturing Organization |
|-------------|----------------------------------|---------------------------|
| Not necessarily structured by considering the efficiency of the organization, and sometimes structured based on excellent design and price competitiveness. | Mostly structured by internal members of the company with the same business interests. |

| Working method | Construction Project Organization | Manufacturing Organization |
|----------------|----------------------------------|---------------------------|
| Performed in the way that participants, such as the client, designer, and constructor have been operating, through traditional contractual relationships. | No need to be performed in the traditional way of working, as there are no contractual relationships among the members. |

Table 1. Comparison of construction project organization and traditional manufacturing organization.

Due to scale-up and convolution of construction projects, as well as the increasing
introduction of collaborative project implementation techniques such as CMAR, IPD, and
OSC, an individual or organization cannot retain the knowledge and capabilities needed to manage all issues that occur during project execution. Thus, there is a growing emphasis on collaboration among different organizations to achieve project goals [65]. There may be two reasons for this. Firstly, most of the project-related information that affects the project performance is generated in the design, development, and construction documentation stages. Depending on how accurate the information generated in these stages is, and how well it reflects the project conditions, schedule delays and cost overrun can be avoided by preventing the occurrence of unexpected events, such as design change, and high project performance can be achieved. Secondly, this organizational knowledge creation process entails a continuous organizational development among participating individuals and organizations. The quality of information generated by the project organization is dependent on the levels of the organizational knowledge creation process and the organizational development process (Figure 2).

![Organizational knowledge creation process in a construction project](image)

Figure 2. Organizational knowledge creation process in a construction project [6].

In recent years, the increasing utilization of information in the construction project implementation process has resulted in the growing importance of information exchange and collaborative work within the organization [5]. For effective construction project organization performance, the following factors were determined to be essential: (1) commitment from top management, (2) team leadership, (3) a focus on goals and objectives, (4) effective communication, and (5) trust and respect [66]. However, the following issues arise from the characteristics of the temporary organization: (1) unclear detailed roles, responsibilities, and work procedures, (2) adversary relationships, and (3) unfamiliarity among team members [2], which prevent effective communication, cooperation and information sharing, resulting in construction delay and cost overrun [67].

3.2. Project Organization as Complex System

Some studies have been conducted to view an organization as a social and organic system, rather than a mechanical system [7]. The organic organizational view is based on the fact that an organization is a being of creation, development, change, and decline, rather than a mere construct made up of sub-elements. The organic organizational view has characteristics that are contrary to the conventional mechanical organizational view (Table 2) [68]. For example, work in the latter proceeds by decisions and instructions according to a strict hierarchical system, whereas the horizontal and collaborative work method of former view prevails according to a distributed network organizational structure. Table 2 displays the differences in detailed characteristics between these two views. The construction project organization is created with a special purpose for each project, and can
be characterized as an organic organization with experts from various fields of work, based on a collaborative relationship.

Table 2. A comparison between mechanical and organic organization views.

|                        | Mechanical Organizational View                                      | Organic Organizational View                                      |
|------------------------|---------------------------------------------------------------------|-----------------------------------------------------------------|
| Suitable environment   | Suitable for environments that concern stable problems.            | Suitable for dynamic problem solving with new problems and unpredictable requirements. |
| Collaborative working method | A method of subdividing tasks according to detailed functional differentiation. | A method of contributing to common problem solving through individual expertise and experience. |
| Organizational structure | Management and communication take place from top to bottom, through hierarchical relationships. | Management and communication take place horizontally, through the network structure. |
| Organizational knowledge | Organizational knowledge is located only at the top of the organization, which governs all decision-making. | Organizational knowledge is present in the organizational network, which becomes a special center of temporary management and communication. |
| Communication method    | Work-related communication mainly takes place vertically by orders passed from superiors to subordinates. | Communication takes place in a way that members of various ranks have business-related discussions horizontally and in a two-way direction. |
| Business management type | Business management is mainly made by decisions and instructions from superiors. | Business management is performed in the way of exchanging information and discussing matters with each other, rather than receiving decisions and instructions. |
| Important value         | Fidelity to work and obedience to superiors are important, and attachment to the inside of the organization is more highly recognized than professional knowledge and experience. | Contribution and responsibility to work are more important than simple fidelity and obedience, and professionalism is highly recognized, as outside the organization. |

The emergence of the organic organizational view is related to the recognition of the limitations of reductionism, which has been dominant in natural sciences over the past several decades. Reductionist thinking refers to a way of thinking that attempts to understand a system via simplification or division into sub-elements, under the premise that a system is a simple combination of sub-systems or sub-elements. Reductionist thinking does not consider the effects of relationships or interactions among sub-elements within the overall system. It can be effective when the overall aspect of the system is considered, or when the interaction among sub-elements is weak, with a negligible effect on the overall system.

However, reductionist thinking is not valid when the behavior of a system is induced by the interaction of sub-elements, or when the expressed system properties are greater than a simple combination of sub-elements [69]. This type of system is called a complex system. Complexity within this system occurs when the dependencies between components act as an important factor in determining the behavior of the system [8]. As previously described, the behavior of a complex system is significantly different from the characteristics of its constituent elements, which cannot be understood by dividing the system into sub-elements.
The organic organizational view regards the organization in an unpredictable dynamic situation and as a complex system, in that it emphasizes the system behavior by interaction among sub-elements. According to the organic organizational view, each member with different characteristics resolves problems through two-way horizontal communication and work methods in a network-type structure. In addition, organizational knowledge is internalized in the network, and decisions are made through mutual consultation, rather than via the top-down approach of a mechanical organization. Ultimately, the systemic behavior of the organization occurs through cooperation and communication at the lower level among the members of the organization, and is created by interaction rather than by the characteristics of the individual members.

3.3. Impact of Organizational Dynamics on Project Performance

There is wide recognition of the importance of the organizational aspect in project management, and its impact on the overall project. However, organizational factors in project planning and execution are regarded as fixed factors, or reflected in an implicit manner. For example, the duration of work is typically calculated based on the previous work productivity data through a correction process, according to the manager’s experience and judgment during the process of calculating the construction duration when establishing a project process plan. Moreover, various factors including organizational factors are considered in the correction process by the manager’s subjective judgment, depending on project situation (Figure 3). This standardized method may be suitable for implementing simple or repetitive projects, while complex large-scale projects could produce invalid results, due to the difficulty of forecasting due to greater complexity and uncertainty.

The current planning and control methods of large-scale construction projects do not explicitly consider organizational aspects. Project managers are often overly optimistic about issues such as organizational efficiency, information sharing, and collaboration, without a clear reasoning process. Managers in large-scale complex projects tend to make wrong decisions due to limited knowledge and incomplete information, experiencing difficulties in communicating, sharing knowledge, and facilitating teamwork among organizations with different knowledge/experiences/goals/protocols. As a result, there is a high likelihood of insufficient planning reliability in tasks such as proposal preparation, resource management, tracking delays and changes to orders, approving progress payments, and cooperation with subcontractors, all of which are performed under current construction planning and management methods.

![Figure 3. Duration calculation process for construction work.](image-url)
Ballard [70] defined plan reliability as the degree to which an established plan is consistent with actual project execution, positing that a high level of plan reliability can be achieved when all factors affecting performance are considered in an explicit and systematic manner. These include (1) accuracy of drawings and documents, (2) common understanding of project execution among participants, (3) suitability of schedule, (4) space availability for stacking materials and utilizing equipment, and (5) weather. It is important to raise the plan reliability through the collaborative process in the initial stage of the project by enhancing the efficiency of project management and overall performance. However, traditional project management techniques fall short of a sufficient level of plan reliability, due to neglecting the previously described factors.

Son and Rojas [6] quantitatively analyzed how manager optimism bias toward organizational factors can affect the overall project performance, using the system dynamics technique. They pointed out that construction project managers tend to have an optimism bias (i.e., they are overconfident about their planned actions), arguing that this can negatively affect project performance, and that, as previously described, most of the project-related information is generated by the interaction between organizational members in the pre-construction stage. The factors that impede project performance, such as design errors, construction defects, and design changes, can be minimized in the pre-construction stage through the continuous organizational redesign process, according to business needs. If the manager of a complex construction project has an optimism bias toward the organization without a successful organizational redesign process, it leads to unrealistic project planning and execution, and, in turn, negative effects on the project performance.

4. Computer Simulation of Construction Project Organization: Experiments and Results

4.1. Computational Organization Simulation

The need to understand organizations from a complex system perspective has moved researchers into the realm of computational modeling and simulation. The computational modeling approach has been used for developing and testing organizational theories that might be too complex to be analyzed by conventional techniques such as equation-based models [71]. There are several advantages to investigating with a computational model for developing and testing organizational theories. These advantages include general ones [72] which are obtained when developing any type of simulation model, such as manufacturing system simulation and special ones for organizational simulation [71]:

- The process of developing a formal model drives researchers to be precise about relationships among entities, to make implicit suppositions explicit, and to describe systematically and thoroughly the mechanisms by which entities and relationships change;
- A computation model can help in grasping how the system works, rather than how individuals think the system would work;
- A computation model can help develop mechanism-based theories rather than variable-based theories;
- Analysis using a computer model helps researchers to derive predictions from their models without error;
- A computation model can be tested without using inputting real resources;
- A number of what-if scenario experiments can be conducted without additional effort and resources;
- Various aspects of understanding about a system under investigation can be obtained during model manipulations.

ABS can effectively explore an organization as a complex system [57]. ABS is a method for understanding the overall behavior of a system through a phenomenon that is expressed through the dynamic interaction of agents with autonomy and diversity. It is useful when (1) members’ actions are non-linear, (2) members’ actions are based on memory, or (3) interactions between members show diversity, and induce network effects [73].

This ground-up view of ABS on complex systems is suitable for systematic study of complex systems, and it has been widely utilized in various fields, including sociol-
ogy [51,74,75], economics [76], industrial engineering [48], computer science [47], business administration [46,49,50,77], anthropology [78], and physics [79].

The increasing use of ABS is attributed mainly to its realistic, ground-up view of complex systems. In particular, each agent in ABS is defined as identifiable, situated in an environment, goal-directed, autonomous, and able to learn [57]. Each agent in ABS behaves and evolves while interacting with other agents and the environment according to a defined protocol, and this process results in the pattern of the overall system. This ground-up approach of ABS is most suitable for systematically exploring complex systems characterized by high levels of localization and distribution [80]. The major characteristics of ABS are as follow:

- **Descriptive realism**: ABS is expressed with explicit computational formalisms. Once it has been fully described, the predictions are clear, quantitative and objective. It is a universal feature that entities being modeled in the target system are mapped onto corresponding agents in the ABM. Accordingly, the boundary of the entities and their interactions correspond to those of the agents [81].

- **Process-oriented method**: Agents’ processes, such as how they recognize an environment, how they use information, and how they interact with each other, must be explicit and well specified. In analytic models which rely on only a few parameters to represent problems, such issues are often ignored. The process-oriented thinking often illuminates the key characteristics and processes that must be considered, and points us toward new perspectives from which to make theoretical advances [8].

- **Generative method**: ABS inherently produces constructive proofs to propositions. The ability to fully generate replications of phenomenon from the ground-up provides new ways of obtaining new insights and understandings [8].

- **Relevance and reliability**: Equation-based approaches have often been characterized as ensuring reliability by strengthening the formal modeling steps. Improving the reliability of the formal modeling may be accomplished at the expense of its relevance to the target systems, because of the augmented abstraction to the target systems. The more abstract the model, the more reliable but the less relevant. ABS allow the application of computational models to social systems without the loss of relevance, due to its descriptive realism [82].

- **Greater contingency in inference**: Because ABS is indeterministic, path-dependent, and emergent, it can generate diverse results. Therefore, performing many runs of simulations and averaging the results may merely end in misleading artifacts. Single runs of ABS are not representative of the system’s general behavior, and thus examining each single run is often required to distinguish what is happening in each, so that one can begin to determine how to classify the simulation trajectories [82].

- **Multi-level analysis**: ABS provides true bridging explanations that link two distinct levels of analysis, the properties of individual agents and the emergent system-level behavior. ABS shows how coherent group-level structures can spontaneously emerge without leaders ordering the organization, and sometimes despite leaders’ effort [81].

- **Adaptive and boundedly rational agents**: A long-standing question of social scientists is how restrictions on the ability of agents to rationally process information impact the behavior of social systems. The flexibility of ABS and development of computational study enables ABS to be suitable for incorporating agents who are boundedly rational and can adapt their behaviors [8].

- **Heterogeneous agent**: Many social and economic theories and equation-based tools have developed with an assumption of homogeneous agents. Homogeneity is not a feature which can be observed in the real world. Given sufficient level of agent heterogeneity, the aggregate behavior of systems may no longer depend on the various details of each agent. ABS is able to incorporate heterogeneous agents who have a different set of properties and behave differently [8].
4.2. Simulation Development Process

A standardized format or procedure for developing ABS, due to its characteristics, has not been completely established. Typically, the development process of ABS is similar to that of object-oriented programming. For this reason, ABS is sometimes considered to be similar to object-oriented simulation, but the agent of ABS is distinct, in that it has purpose, memory, and learning ability [83]. Thus, the ABS development process is more complex, typically undergoing the following procedure: (1) defining the agent’s type, characteristics and internal logic, (2) establishing the behavioral logic with which the agent interacts, and (3) defining the environment in which the agent is present (Figure 4).

![ABS development process diagram](image)

Figure 4. ABS development process.

1. Defining the agent’s type, characteristics and internal logic

The agent is the most basic and essential element for making decisions in a simulation. Agents can be anything independent of real-world systems, such as software, models, or people, and can be further defined by describing their characteristics and behavior. Agents have different characteristics, and behave dynamically. The internal logic of the agent is defined in various manners, depending on the complexity of the model, the information required for decision-making, and the capacity of memory (Figure 5).

![Agent and environment diagram](image)

Figure 5. Concept of an agent’s internal logic.

A formulation of the internal logic similar to the real one is crucial for realistic simulation, by abstracting the complex decision-making process. However, a simple internal logic is sufficient for modeling to represent complex phenomena, and can provide useful understanding and intuition about the target system. A simple definition of internal...
logic enables developers to shorten the time required for development, verification, and confirmation, by focusing on the core mechanisms that determine the behavior of the system. Agents created by complex internal logic may be highly realistic in recognizing external stimuli, making effective decisions under complex situations, and learning, based on feedback on their actions, whereas those with simpler internal logic exhibit a better ability to interpret phenomena.

2. Establishing the behavioral logic with which the agent interacts

Behavioral logic for interaction between agents is defined depending on the purpose of developing the simulation, which includes a method for agents to interact with each other, a method to communicate and cooperate, and the purpose and motivation for communication and cooperation. As previously described, because a standardized format or procedure for this process is not completely established, it proceeds according to the characteristics of the system being modeled. As with defining the agent’s internal logic in the previous step, there can be a simple behavioral logic that simply responds to information and external stimuli, and a complex behavioral logic such as acting for its own purpose. For example, Yu, et al. [84] defined the behavioral logic among developers with several equations, in simulating dynamic relationships between open-source software developers, whereas Hanaki, et al. [85], defined in detail (in the simulation study of collaboration process within social networks) the interactional behavioral logic among agents, based on the concepts of expected marginal return, marginal cost, and trust.

3. Defining the environment in which the agent is present

The environment in the simulation is an abstraction of the real-world environment, in which an agent is present in interaction with other agents. The environment can be an organization, a software development group, a supply chain, or a transportation system, depending on the system being modeled. The interaction between agents and the environment results in changes in both the characteristics of the agent and the state of the environment. When the agent receives information or a stimulus from the environment, it evaluates it according to the internal behavior logic, makes an appropriate decision, and takes action. These series of steps constitute one cycle within the ABS, and continue until the simulation ends.

4.3. Agent-Based Simulation of Construction Project Organization

This simulation was developed by extending the concept of a collaboration game developed by Jackson and Watts [86], and an early version of the simulation was introduced in Son and Rojas [87]. The project organization was modeled as a network of members pursuing their own goals, which processes information dynamically. Members modeled as agents each have different characteristics, and continue to engage in social activities to exchange information in collaboration with other agents, to achieve maximum payoff. However, the agent is a short-sighted entity, capable of recognizing the entire network, and makes decisions based on available information alone. Agent performance is enhanced when it can acquire information or assistance necessary for work from an accessible partner on the network, and the agent continues to engage in social activities and decision-making to meet new partners. The decision-making of an agent at this lower level is affected not only by the characteristics of the entire network, but also by those of the local network of each individual. Furthermore, the characteristics of the entire network at the upper level are induced by the interaction between the agents at the lower level. The simulation was developed in Java programming language by using Eclipse, an integrated development environment.

4.3.1. Simulation Descriptions

1. Individual Characteristics of Agents

The members of the project organization were defined as agents with different levels of sociability (a characteristic of the agent’s degree of amicability, which affects the agent’s
likelihood of meeting new potential partners) and familiarity. Agents participate in a virtual social interaction in every cycle of the simulation. The higher the sociality, the more often they participate in social interactions and meet potential partners, whereas the lower the sociality, the less often they do so. Familiarity is a characteristic that indicates the degree to which an agent is close to other agents on the network, which affects the process of a potential partner becoming a partner engaging in collaboration and information exchange. Potential partners met in the process of social interaction are determined by a function of familiarity, and the more often they meet, the higher the familiarity between each other is maintained.

2. Payoff

To improve their performance, agents are constantly searching for partners on the network. When an agent meets a potential partner during social interaction, the agent decides whether to collaborate with the candidate. Collaboration will be determined by comparing the results obtained from the current partners with those from the new partners. If the agent can achieve higher performance through a new potential partner, the candidate will either become a new partner or replace the current partner. The performance evaluation method was defined based on the production function of Cobb and Douglas [88] (Equation (1)). Performance tends to rise as an agent benefits from necessary information and assistance from a greater number of partners. Performance is affected by the number of partners and maintenance costs:

$$u_i(g_t) = \left((\omega_{i,t} + 1)^a\right)^{b_{i,t}} \times \left((\beta_{i,t} + 1)^b - \sum_{ij \in g} c_{ij}\right)$$

where $u_i$: payoff of agent $i$, $g_t$: network at time $t$, $\omega_{i,t}$: number of insider partner of agent $i$ in $g_t$, $\beta_{i,t}$: number of outsider partner of agent $i$ in $g_t$, $a$: elasticity of $\omega_{i,t}$, $b$: elasticity of $\beta_{i,t}$, $c$: maintenance cost.

3. Collaboration

However, a high number of partners does not necessarily result in high performance, and performance is influenced by the synergetic effects from various relationships, as well as the cost of maintaining the relationships. Agents can improve their performance when they acquire various information from outside partners from other organizations, as well as from inside partners within the organization to which they belong. This view is based on research findings, such as results for those who possess a dominant position accessible to a variety of work-related information on the network [89].

4. Maintenance cost

An agent must pay a corresponding fee to maintain the relationship with the partner. Here, cost was defined as a concept that includes monetary value, as well as all sacrifices made to maintain a relationship, such as time and effort [90]. The cost of maintaining a relationship with an outsider partner was assumed to be greater than that of maintaining a relationship with an insider partner.

5. Payoff maximization

When agents meet potential partners, they explore the best possible outcomes achievable therewith. Agents increase their performance by obtaining new partners or replacing existing partners with new ones. However, agents, due to their perceptual limitations, can have only a limited number of peers, and they cannot replace multiple partners at once.

6. Mutation generation

Random partner replacement can occur through the stochastic variant generation process after each cycle. The variant generation process in the ABS is required to escape from the static fixation that may occur in evolutionary models [86]. The variant generation process is implemented through a considerably low variant generation probability, which reflects bounded rationality, such as the agent’s mistake in evaluating the performance.
of a partner, termination of the relationship due to insufficient cost, or any shift in the relationship due to external factors.

4.3.2. Experimental Results and Discussions

The experiment stage assumed that two different types of agents form a project organization, with the total number of agents set to 100. Sociality was established using a normal distribution. Each agent has a different sociality value, and meets potential partners three times every ten cycles on average. The familiarity with the outsider was set lower than that with the insider, which was varied, depending on experiments creating various experimental cases. Similarly, the maintenance cost with the insider was set to 0.1, and that with the outsider was set to higher values, such as 0.2, 0.5, 1.0, for the experiment. The simulation was run until the entire system behavior reached a stable state, and 100 trials of simulation were run for varied conditions.

(1) Agent-level network formation

As the simulation proceeded, the agents underwent a process of social interaction to build up the relationships with potential partners. Most agents formed a partner network within a certain time period to boost their performance, eventually achieving the maximum performance. The network diagram shown in Figure 6 shows that only a few agents have partnership at $t = 1$, while most of the agents have partnerships at $t = 21$ in the simulation, where familiarity with insider/familiarity with outsider/maintenance cost with insider/maintenance cost with outsider is set to 100/10/0.1/0.5 respectively. Partnerships are indicated by a solid line connecting the dots. The majority of agents achieved the maximum outcomes in each cycle by connecting to partners.

![Figure 6. Individual network development.](image)

(2) Effects of agent characteristics on network formation

The familiarity with the insider affected the growth pattern of organizational networks as well as the performance of agents. In cases where the familiarity with the insider was high, the agent had no opportunity to meet the potential outsider partner, and as a result, the maximum performance required more time to achieve than in cases where the familiarity with the insider was low. The level of familiarity, combined with the effect of maintenance cost with outsiders, showed various patterns of the network. Firstly, when the maintenance cost with the outsider was low (facilitating the creation and maintenance of relationships with an outsider partner), the agent strived to boost the performance by forming a relationship with the outsider partner, and this state continued. The simulation results indicated that when the maintenance cost with the outsider is as low as 0.2, and the familiarity with the insider is 50, 100, and 150, all agents, on average, could have the
number of insider and outsider partners that achieve the maximum performance in cycles 69, 93, and 100 (Figure 7).

![Figure 7](image-url)

**Figure 7.** Average number of partners: (a) familiarity with insider: 50, maintenance cost with outsider: 0.2, (b) familiarity with insider: 100, maintenance cost with outsider: 0.2, (c) familiarity with insider: 150, maintenance cost with outsider: 0.2.

When the maintenance cost with the outsider was as high as 1.0, maximum performance could be achieved in the same cycle at different levels of familiarity with the insider. This is because the cost of creating an outsider partner offsets its effect on enhanced performance, resulting in a level of performance that can be achieved only with an insider partner (i.e., without undergoing the process of connecting to an outsider partner).

Social agents participated in social interactions more frequently than non-social agents to achieve maximum performance earlier during the process. For example, a highly social agent forms a partner network in the first three cycles to achieve maximum performance, whereas a relatively poor social agent network formation was delayed, connecting to the first partner in the 19th cycle, and achieved the maximum performance in the 23rd cycle.

3. Achievement of payoffs by agent

The performance of the agents was greatly affected by their sociality. High social agents intended to boost their performance by meeting potential partners more frequently than poorly social agents. Thus, the highly social agent achieved the maximum performance in a short time period, whereas the opposite case required a longer time. The agent with the highest performance in the shortest time period achieved the payoff of 1.441, by connecting to three partners in the first three cycles. In contrast, another agent required 23 cycles to achieve the same performance. For example, agent 19 formed six partnerships, changed partners three times, and reached the highest payoff at $t = 19$ after experiencing a payoff drop at $t = 12$. However, agent 89 experienced a payoff drop due to the change of partners after achieving the highest payoff, and this agent re-formed the partnership (Figure 8).

![Figure 8](image-url)

**Figure 8.** Change in agents’ payoff.

4. Formation of cohesive subgroups

When the maintenance cost with outsiders is high, a cohesive subgroup appeared within the organization (Figure 9). To measure the degree of occurrence of cohesive subgroups on the network, the clustering coefficients were calculated for each result [91].
Findings showed that higher the maintenance cost with the outsider, the higher the clustering coefficient, indicating a stronger tendency of cohesive subgroup generation. In addition, when the maintenance cost with the outsider was high, the size and average distance of the network increased. As previously described, the increase in performance by connecting to an outsider partner was offset by the high maintenance cost thereof, resulting in an insider partnership alone. As a result, the corresponding agents failed to reach the maximum performance.

Figure 9. Cohesive subgroup formation.

5. Conclusions

This study investigated how organizational factors affect project performance during a construction project, and developed and presented ABS as a means to explore the process of forming a collaborative network within the construction project organization. As a result, the author found that manager optimism bias toward organizational factors leads to unrealistic project planning and execution, ultimately resulting in negative effects on project performance. To resolve this issue, this study introduced a complex system perspective that views an organization as an organic organization, and presented a method to dynamically understand organizational elements by using ABS.

This study is significant, as it enhances the understanding of the organizational aspect of a construction project, and presents a new direction to reflect the organizational aspect in the project management process. Firstly, this study presents a new perspective on the network formation process within an organization during a construction project. Previous studies did not properly reflect the characteristics of the project organization, which is a temporary organization, by viewing the project organization from a mechanical perspective. This study views the process of collaboration and information-sharing occurring within the organization of a construction project from the complexity system perspective, and describes the formation process of organizational dynamics occurring within the organization. In addition, this study explores whether the organizational dynamics occurring within the construction project organization could affect overall project performance. Previous studies analyzed past performance data, leadership, and partnering regarding project organization performance from a static perspective. In contrast, this study views the project performance as a dynamic development process via the interaction of members, and describes the process in which cooperation and information sharing within the organization affect the performance. Lastly, this study presents the ABS method and related cases as an analysis method that can grasp the organizational dynamics formation process. The ABS is highly advantageous in exploring complex systems, such as project organization. The results of this study will provide some direction that can reflect the results of organizational analysis using ABS in project management, in that project organization can be viewed from the agent (member) from the ground-up viewpoint, and that the organization’s behavior can be observed through the interactions among agents.
However, this study has limitations, in that the organizational analysis method using ABS presented here does not reflect the detail of the construction project implementation process. The progression of construction projects can vary, depending on performance conditions according to the characteristics of the project and the execution organization. Moreover, various factors influence the formation process of a project organization, such as individual characteristics, expertise, knowledge, experience, work procedures, and the communication methods of each member. Follow-ups should proceed in a direction that reflects the characteristics of these projects and the diversity of members. This study also has a limitation in that it has not verified the validity of the simulation for actual projects. In future studies, it is necessary to conduct empirical studies on actual projects in order to verify the effectiveness of the simulation.

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