AN AGENT-BASED PLATFORM FOR DECISION MAKING ON THE GREEN RETROFIT OF PUBLIC BUILDINGS

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CERTIFICATE OF ORIGINALITY

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Signed

LIANG Xin

Abstract

In the last two decades, energy consumption in China has increased rapidly due to fast urbanization and industrialization. In 2010, China replaced the United States as the largest energy consumer, accounting for more than 20% of the total global energy consumption. The building sector was responsible of 40% of total energy consumption and 15% of greenhouse gas (GHG) emission. Within this sector, the energy consumption per square meter in public buildings is 5-15 times of that in residential buildings. In addition, most energy consumption occurs during the actual occupancy operation stage rather than during the construction stage. Therefore, green retrofit, which can improve the energy efficiency of public buildings, plays an important role in energy saving and GHG reduction.

The decision making on green retrofit is more complex compared to new green buildings, since green retrofit involves more restrictions (e.g., the structures and locations of buildings) and stakeholders (e.g., tenants and facility managers). Most previous studies investigated the decision making on green retrofit from the technical, economic, and environmental perspectives. Few studies, if not none, have investigated the decision-making behaviors of the key stakeholders and their different interaction relationships under different circumstances. Therefore, the behaviors and strategies of stakeholders in decision making on green retrofit remain unexplored areas.

The primary aim of this research is to examine whether an agent-based platform that models decision-making behaviors of stakeholders can support decision making on green retrofit of public buildings.

The specific objectives of this research are as follows:

(1) To analyze the relationship of stakeholders and their priorities in green retrofit through a two-mode social network analysis.

(2) To build a model of decision-making behaviors based on game theory for optimizing decisions of key stakeholders on green retrofit.

(3) To develop and validate an agent-based platform on the basis of the proposed model to support decision making on green retrofit.

This study reviewed previous studies related to green retrofit and summarized the state-of-the-art research in this area. The stakeholders and their characteristics were identified by literature review and interviews. A two-mode social network was developed to analyze the stakeholder relationship and a game model was built to optimize the decision making of stakeholders on green retrofit. Based on the model, an agent-based platform was developed, which can facilitate decision making on green retrofit. To validate the platform, the policies, launched by the Shanghai and Shenzhen local governments for energy efficiency retrofit of public buildings, were simulated on the developed platform.

The key findings obtained from this study are as follows. First, a two-mode network of stakeholders was developed to analyze the relationship and priority of stakeholders in green retrofit projects. Second, a game theory-based model was built, which can explain the reasons for stakeholder decision-making behaviors in green retrofit. The split incentives between owners and tenants were identified as main barriers of green retrofit projects. The proposed model can optimize the decision making on green retrofit by balancing benefits among key stakeholders. Third, an agent-based platform for supporting decision making on the green retrofit of public buildings was developed on the basis of the proposed model. A sensitivity analysis was conducted and the results showed the platform is robust. The factors influencing decision making on green retrofit were investigated and the results showed that the two factors (i.e., the cost of green retrofit and the energy price) influence the decision making on green retrofit most significantly.

This study made original contributions to the decision making on green retrofit from both theoretical and practical perspectives. From the theoretical perspective, first, this study proposed an innovative method to improve the understanding of stakeholder relationship through a two-mode social network analysis. Second, this study first analyzed the behaviors and strategies of the stakeholders in green retrofit through a game theory-based model. From the practical perspective, this study developed an agent-based platform to support decision making on green retrofit, which can facilitate information sharing, simplify the process of decision making and improve the collaboration among stakeholders in green retrofit. This is the first integrated platform designed for both the government and other stakeholders (e.g., owners, tenants and facility managers). For the government, the platform can provide customized policy suggestions for different types of buildings. For other stakeholders, it can provide decision-making support for an individual green retrofit project. In summary, the proposed agent-based platform is an effective tool to assess costs and benefits of green retrofit projects, support decision making and provide policy suggestions, and consequently, it can further promote green retrofit of public buildings and reduce energy consumption and GHG emission.

Publications

Journal Papers:

1. Liang, X., Hong, T., & Shen, G. Q. (Accepted) Improving prediction of building energy use with occupancy data. *Applied Energy*
2. Liang, X., Peng, Y., & Shen, G. Q. (Accepted) A Game Theory Based Analysis of Decision Making for Green Retrofit under Different Occupancy Types. *Journal of Cleaner Production*
3. Liang, X., Hong, T., & Shen, G. Q. (2016) Occupancy data analytics and prediction: a case study. *Building and Environment*. 102, 179-192.
4. Liang, X., Shen, G. Q., & Bu, S. (2016) Multi-agent systems in construction: a ten-year review. *Journal of Computing in Civil Engineering*, doi:10.1061/(ASCE)CP.1943-5487.0000574.
5. Liang, X., Shen, G. Q., & Guo, L. (2015). Improving management of green retrofits from a stakeholder perspective: a case study in china. *International Journal of Environmental Research & Public Health*, 12(11), 13823-13842.
6. Bu, S., Shen, G. Q. P., & Liang, X. (2015). Literature Review of Green Retrofit Design for Commercial Buildings with BIM Implication. *Smart and Sustainable Built Environment* Vol. 4 Iss: 2, pp.188 - 214
7. Guo, L., Bu, S. S., Zhu, Z. G., Su, Y. F., & Liang, X. (2014). The research of BIM theory applied in decision making of commercial building green retrofit. *Applied Mechanics & Materials*, 667, 68-71.

Conference Papers:

1. Liang, X., Shen, G. Q. P., & Bu, S. (2014). A Bayesian Approach for Best Practice Recommendations in Collaborative Designs of Construction Projects. *ICCREM 2014 Smart Construction and Management in the Context of New Technology* (pp.721-732). ASCE.
2. Bu, S., & Shen, Q. P & Liang, X. Conjoint Analysis in the I3-E GRD framework of Green Retrofitting commercial buildings. *Proceedings of International Conference on Sustainable Development in Building and Environment 27-29 July 2015*, Reading, UK

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Chapter 1 Introduction

1.1 Introduction

This chapter outlines the basic research proposition of this study, including the research background, research questions, research scope, and research aim and objectives. The overall research design and structure of the thesis are also presented. Finally, the value and significance of the research are highlighted.

1.2 Research Background

The building sector was responsible of 40% of total energy consumption and 15% of greenhouse gas (GHG) emission around the world (Hong et al., 2015). In the United States (US), buildings consume approximately 50% of the total energy and 40% of GHG emissions (EIA, 2010), while in Europe, the ratio is approximately 40% (Kashif et al., 2011). In the last two decades, building energy consumption has continuously increased, particularly in developing countries. In China, building energy consumption increased by more than 10% annually (Xu et al., 2011). Public buildings have high energy use intensity, which can reach 300 kWh/m^2 and 5–15 times of that in residential buildings (THUBERC, 2007). Therefore, public buildings play an important role in the total energy consumption.

In the life cycle of a building, more than 80% of the energy consumption occurs during the actual occupancy operation stage rather than during the construction stage (UNEP, 2007). In addition, (Carbon Trust, 2008) indicated that 60% of the buildings that will be standing in 2050 have already been built. However, green building topics have focused mainly on the construction phase of new buildings rather than on the operation and retrofit of existing buildings.

Owing to its essential influence on energy consumption and GHG emission, green retrofit for existing buildings should be given due attention. “Green retrofit” can be defined as the incremental improvement of the fabric and systems of a building with the primary intention of improving energy efficiency and reducing carbon emissions. It can also refer to other terms in literature, such as refurbishment, rehabilitation, modernization, renovation, improvements, adaptation, additions, repairs, and renewal on existing buildings (Ali and Rahmat, 2009). However, routine maintenance and cleaning work are excluded (Quah, 1988).

Green retrofit for existing buildings is emphasized by governments all over the world. In 2005, the US government passed the Energy Policy Act (EPA) and Executive Order 13423, which require retrofitting 15% of the total number of existing buildings to improve energy efficiency by 2015 compared with the 2003 baseline (EPA, 2005). Approximately 30 billion US dollars were earmarked to conduct green retrofit projects for the existing buildings and facilities. In 2010, the UK government launched the Carbon Reduction Commitment (CRC) Energy Efficiency Scheme to save 1.2 million tons of CO_2 emissions annually by 2020. This scheme motivates consumers to consider energy efficiency options and invest in building retrofit projects. The Chinese government has also introduced various policies. China's 12th Five-Year Plan stipulated that 400 million m^2 residential buildings and 60 million m^2 public buildings were to be retrofitted as pilot projects between 2011 and 2015 to improve energy efficiency of buildings.

By contrast, green retrofit projects remain inadequately pursued in industries. After the 2008 global economic recession, this situation was further exacerbated by the challenge of ensuring financial support for retrofitting activities (Menassa, 2011). Some pilot studies revealed that industries are unenthusiastic about green retrofit primarily because of the following aspects: the highly complex design analysis and solution (Davies and Osmani, 2011; Kasivisvanathan et al., 2012; Lapinski et al., 2006), intense interdisciplinary collaboration (Korkmaz et al., 2010; Lapinski et al., 2006), long payback periods (Kasivisvanathan et al., 2012; Menassa, 2011), financial problem (e.g., limited access to capital, high cost, etc.) (Davies and Osmani, 2011; Kasivisvanathan et al., 2012; Xu et al., 2011), lack of retrofit experience (Ali et al., 2008; Kasivisvanathan et al., 2012; Korkmaz et al., 2010), and lack of understanding of the available retrofit technologies (Davies and Osmani, 2011; Miller and Buys, 2008).

Most of the previous research findings were obtained by analyzing the problem from the technical, economic, and environmental perspectives. Only a few studies explored the behaviors of the main stakeholders, who may directly decide whether a building retrofit can be implemented. In practice, owners, tenants, government, and other key stakeholders in green retrofit may have various and conflicting opinions on whether a building should be retrofitted, as well as when and how the retrofit will be implemented. Few studies, if not none, have investigated the decision-making behaviors of the key stakeholders and their different interaction relationships under different circumstances. Therefore, the logic of stakeholders' decision making and how to promote green retrofit remain unexplored areas.

To bridge the aforementioned research gap, this study revealed the logic of decision making on green retrofit by analyzing stakeholder behaviors through a game theory – based model. On the basis of the model, an agent-based platform was developed to optimize the decision making of green retrofit. This study differs from previous ones because it analyzes the decision-making behaviors of key stakeholders under the current market constraints through a theoretical game model and an agent-based platform, instead of identifying the willingness of stakeholders or the retrofit-related problems through a survey method. The platform can be used by governments and building owners for practical green retrofit projects. It can model and simulate the decision-making behaviors of stakeholders under different scenarios with, which is an efficient method for monitoring, accessing, and providing decision-making suggestions. The results of this study provide critical insight into the relationship and behaviors of stakeholders, facilitate the decision making on green retrofit, and improve energy efficiency by optimizing policies.

1.3 Scope of the Study

This study focuses on the green retrofit projects. All the projects improve the energy efficiency of buildings are considered as green retrofit projects in this study, including the fabric and systems of buildings. The results of green retrofit can be evaluated by the improvement rate of energy efficiency, but there is no threshold of the improvement rate. Both large scale retrofit (e.g., renewing the fabric of roof and changing HVAC system) and small scale retrofit (e.g., changing to energy efficiency bulbs) are included in this study.

This study focuses on public buildings. According to the standards of building sector in mainland China (GB50352-2005, GB50268-2011 and GB50378-2014), buildings can be categorized into three types, urban buildings, rural buildings and industry buildings. Unban buildings include residential buildings, public buildings and other buildings. Public buildings can be defined as the buildings for public activities of human, including office buildings, shopping centers, schools, theaters and etc. On one hand, the energy intensity of public buildings is considerably higher than that of residential buildings. On the other hand, the energy use pattern, property ownership, stakeholder relationship, and other influencing factors of green retrofit are different between public buildings and residential buildings. Therefore, an independent investigation on public buildings is necessary.

This study focuses on the decision making regarding whether to retrofit in the initial intention stage. Previous studies asserted that the process of green retrofit projects can normally be divided into five phases: 1) initial intention, 2) pre-retrofit survey and energy performance assessment, 3) design, 4) site implementation, and 5) validation and verification (Lapinski et al., 2006; Ma et al., 2012). Conventional studies related to decision making on green retrofit mainly focused on specific techniques and plans in the design and implementation phases (Ali et al., 2008; Stiess and Dunkelberg, 2013). However, the phase of deciding whether to retrofit buildings, which is before the design phase, is the key phase of a green retrofit (Ma et al., 2012). Numerous buildings have retrofit plans but abort in this phase. Thus, a study on the decision making regarding whether or not to retrofit a building at the first phase is essential.

1.4 Research Aim and Objectives

The primary aim of this research is to examine whether an agent-based platform that models decision-making behaviors of stakeholders can support decision making on green retrofit of public buildings.

The specific objectives of this research are as follows:

(1) To analyze the relationship of stakeholders and their priorities in green retrofit through a two-mode social network analysis.

(2) To build a model of decision-making behaviors based on game theory for optimizing decisions of key stakeholders on green retrofit.

(3) To develop and validate an agent-based platform on the basis of the proposed model to support decision making on green retrofit.

First, a holistic analysis of the stakeholders is conducted and their green-retrofit related characteristics are investigated. This was followed by a network analysis of stakeholder relationship and priorities (Objective 1). Then, a game model is developed to analyze decision-making behaviors of key stakeholders (Objective 2). The key stakeholders identified in the stakeholder analysis are involved in the game theory-based model. The results of the first two objectives together provide a theoretical foundation for the decision making on green retrofit, which are also the inputs and algorithms of the agent-based platform developed in Objective 3. Finally, the policies by the Shanghai and Shenzhen local government for energy efficiency of public buildings are simulated on the platform. The simulation results are compared with the results of the proposed game model to validate the platform. This platform can improve the effectiveness and efficiency of decision making on green retrofit and consequently improve energy efficiency and reduce GHG emission.

1.5 Research Design

This research follows the process shown in Figure 1.1 to realize research objectives.

(1) First, through literature review, research problems are identified and research gaps are clear. This process will lead to Chapters 1 to 3 of the thesis, Introduction and Literature review.

(2) Then data collected from interviews and focus group meetings is analyzed through social network analysis (SNA) and multivariate statistics to identify stakeholder relationship and priorities, including the relationships among stakeholders, related critical success factors (CSFs), and influencing factors of decision making. This process will lead to Chapter 5 of the thesis, Key Stakeholders of Green Retrofit.

(3) According to the results in Step 2, a game model for decision making of key stakeholders on green retrofit can be built, and the optimized solutions of decision making can be provided. This process will lead to Chapter 6 of the thesis.

(4) An agent-based platform for decision making on green retrofit is developed on the basis of game theory. This process will lead to Chapter 7 of the thesis, Agent-based Platform for Decision Making on Green Retrofit.

(5) Finally, some policies launched by the Shanghai and Shenzhen local government for energy efficiency retrofit of public buildings are used to validate the platform, since Shanghai and Shenzhen are two pilot cities of green retrofit policies in China. The results of the proposed game model are compared with the simulation results of the policies in Shanghai and Shenzhen. This process will lead to Chapter 8 of thesis. Findings and conclusions will be presented after this process.

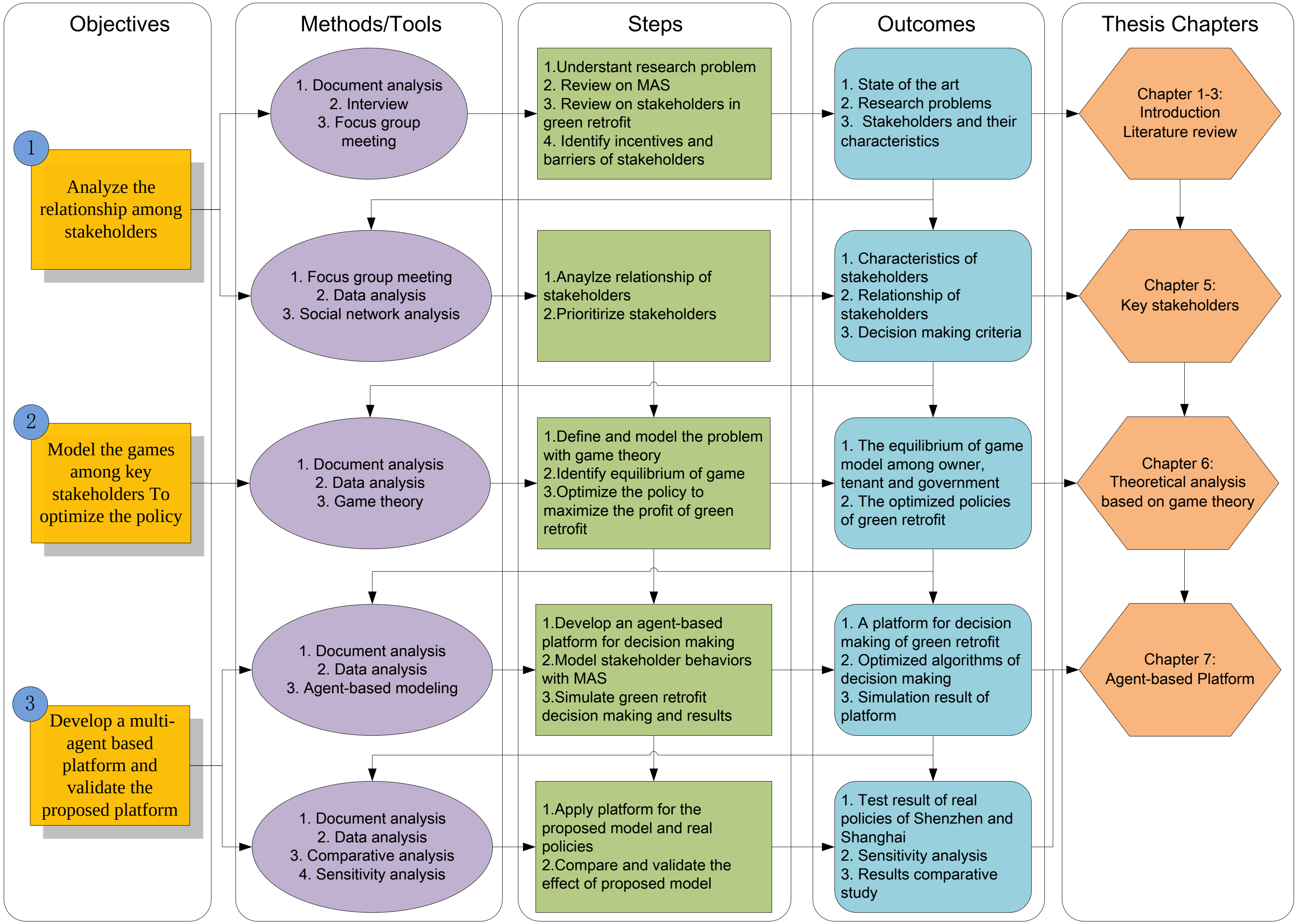


Figure 1.1 Overall framework of the thesis

1.6 Value and Significance of the Research

First, the proposed platform simplifies the decision-making process for green retrofit and improves the collaboration among stakeholders. The current decision-making procedure of green retrofit is shown on the left of Figure 1.2. Normally, a building owner proposes a green retrofit plan to the government on the basis of collaboration with an energy-saving company and the tenants. The government then transfers this plan to a third-party institute for assessment. If the plan passes the assessment, it will be approved by the government and the owner will receive a subsidy and start the green retrofit. If the plan does not pass the assessment, the plan will be rejected by the government. The whole procedure is very long and is divided into several isolated steps. Each step involves different stakeholders with their own information and analysis tools. The proposed platform provides a unified decision support system with multiple functions, including monitoring, assessment and decision support and etc. All related stakeholders can share their information on the same platform. Therefore, stakeholder collaboration can be improved and the decision-making process can be simplified.

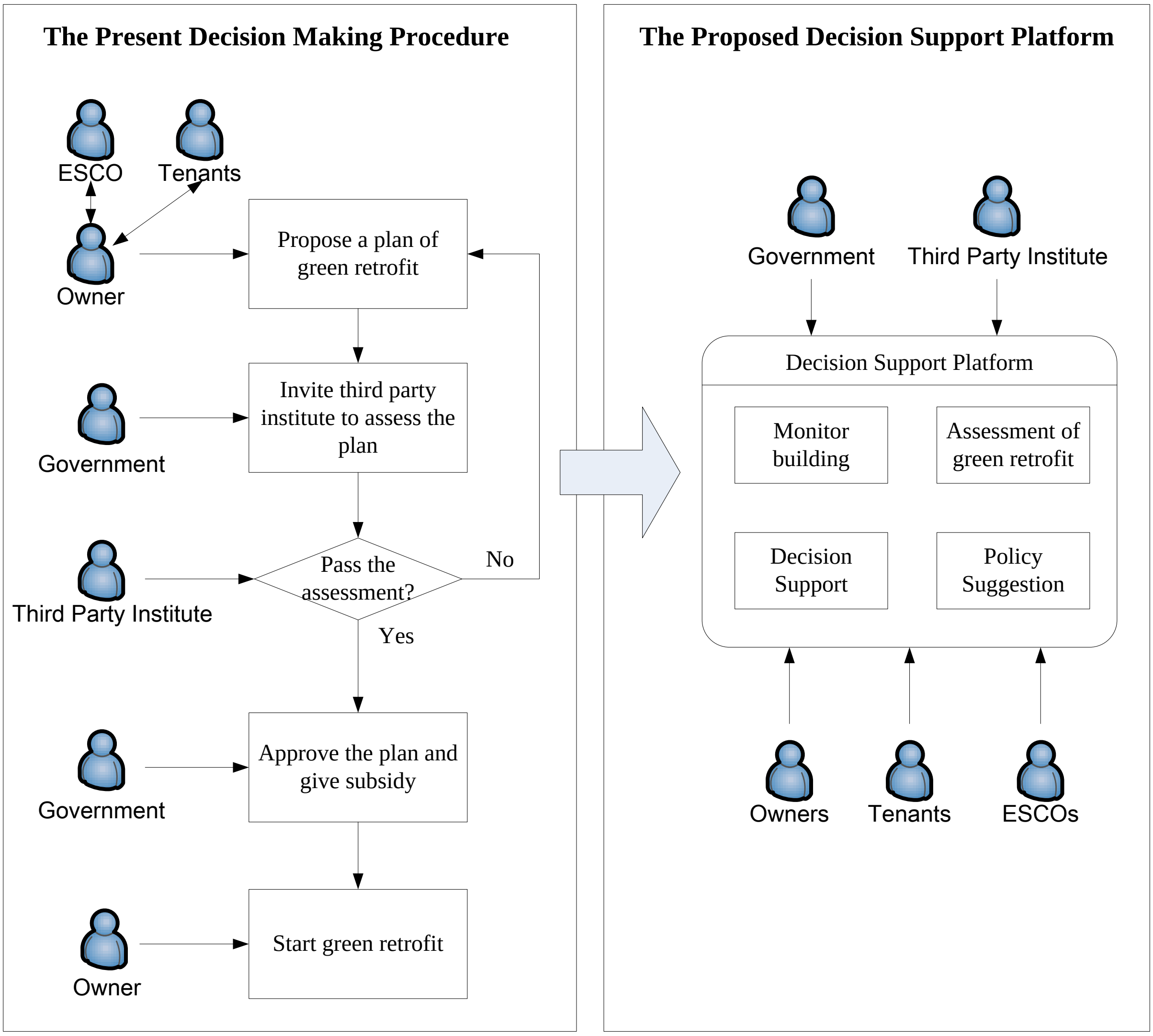


Figure 1.2 Proposed platform compared to the present decision-making procedure

Second, the proposed platform can provide customized policy suggestions for different buildings. At present, the incentive policies are the same for all buildings, an approach known as "one-size-fits-all" policies. For example, the local government of Shanghai provides 40 CNY/m^2 for all public buildings with improved energy efficiency higher than 20%. However, the public buildings vary in age, orientations, occupancy rate, and other aspects. Offering the same incentive to all buildings is therefore inefficient. The proposed platform can offer different policy suggestions for buildings with different characteristics, which will improve the efficiency of policies and the effect of green retrofit.

Third, different from previous studies based on survey data, this study maps the decision-making behaviors in reality to a theoretical model by game theory. Most stakeholders prefer to show the public their positive attitudes rather than their reluctance toward green retrofit. This condition explains why the major cases in existing studies are successful retrofit projects. Constrained by such realities, game theory is adopted to investigate the research question by using a theoretical model and logical deduction rather than an empirical study. The data for the game analysis are primarily obtained from the existing studies and interviews. This process is useful for overcoming the shortages of limited data as a relative value rather than as an absolute value needed in the game analysis.

Fourth, the results of this study have significant practical value at both macro and micro levels. For the macro level, the proposed platform can provide policy suggestions for the government, and the suggested policies can be adapted to different buildings and environments. For the micro level, the proposed platform can offer decision-making support for green retrofit projects, including assessment of the benefits and costs of green retrofit, decision making on whether to retrofit, and selection of the most efficient plan. The proposed platform is based on Java and has a user-friendly interface, which makes it easy to configure and use. If this platform is applied in reality, it will significantly improve the efficiency of decision making on green retrofit.

1.7 Structure of the Thesis

This thesis comprises nine chapters.

Chapter 1 is an overall introduction highlighting the essential information of the whole research, including the background, research questions and objectives, research scope and design, research methods, and structure of the whole thesis.

Chapter 2 presents a comprehensive review of literature regarding green retrofit. Three categories of literature are reviewed: stakeholders and their characteristics in green retrofit, occupancy types of buildings, and drivers and barriers of green retrofit. Moreover, the knowledge gaps are identified to improve the significance of the study.

Chapter 3 presents a comprehensive review of literature regarding multi-agent systems (MASs). Four categories of literature are reviewed: key issues of the MAS related to consensus, advantages and disadvantages of the MAS, applications of the MAS, and development and prospects of the MAS.

Chapter 4 describes the methodologies adopted throughout the research. This chapter first discusses the research framework, followed by an illustration of the detailed methods employed, such as literature review, interview, and focus group meeting. In addition, three major data analysis methods, namely, SNA, multi-agent modeling, and game theory are described in detail.

Chapter 5 presents the key stakeholders of green retrofit identified by using SNA. A two-mode social network model is applied to analyze the relationship among stakeholders.

The closeness of stakeholder relationship is illustrated by a cluster analysis, which classifies stakeholders with close relationship in a cluster. The priorities of stakeholders according to their influence are also identified.

Chapter 6 provides a theoretical analysis of decision making on green retrofit by developing a game model. First, this chapter uses the game model with complete information to analyze the equilibrium solution between owners and tenants. Then, government is added in the game model as a player to improve green retrofit in the next step. An incomplete information model is used to analyze the relationship among government, owner, and tenant. The optimal solution of policies and decisions are provided by the analysis results.

Chapter 7 develops an agent-based platform to facilitate decision making of stakeholders based on the game model in Chapter 6. The results of Chapter 5 and 6 are inputs to the platform. The details of the platform design are illustrated, including architecture, applications, framework, agent definitions, and user interface (UI). A case study is conducted based on the developed platform to validate the platform and the proposed game model. Shanghai and Shenzhen are selected for the case study because they are both pilot cities of green retrofit for public buildings and are first-tier cities in China. The results of the proposed model are compared with the simulation results of policies by the Shanghai and Shenzhen local government. Sensitivity analysis is also conducted to validate the robustness of the model.

Chapter 8 summarizes the primary research findings and examines the achievement of the research objectives proposed at the beginning of the study. The theoretical and practical contributions are highlighted. Finally, the limitations of this study and directions for future studies are discussed.

1.8 Summary of the Chapter

This chapter outlined the overall research proposition, including background information, research questions, research objectives, scope of the study, research design, and significance of this research.

Chapter 2 Literature Review: Green Retrofit

2.1 Introduction

This chapter critically reviews previous research associated with green retrofit. Three categories of literature are reviewed: stakeholders in green retrofit, influence of occupancy types, and drivers and barriers of green retrofit.

2.2 Stakeholders in Green Retrofit

The stakeholders in green retrofit are the people who, directly or indirectly, have vested interests in a building and in the outcome of a potential and ongoing green retrofit project (Gucyeter and Gunaydin, 2012). The main stakeholders identified in literature include owner, tenant, facilities manager, consultant/designer, contractor, subcontractor, supplier, government, financial institutions, energy service companies, environmental organization, professional association, media, public, labor union, and researcher/educator (Gultekin et al., 2013; Juan et al., 2009; Kaklauskas et al., 2008; Kaklauskas et al., 2004; Miller and Buys, 2008; Yang and Zou, 2014), all of which are shown in Figure 2.1. Previous studies asserted that the process of green retrofit projects can normally be divided into five phases, namely, 1) initial intention or setup, 2) pre-retrofit survey and energy performance assessment, 3) design, 4) site implementation, and 5) validation and verification (Lapinski et al., 2006; Ma et al., 2012). Various stakeholders are involved in green retrofit projects in different phases (Figure 2.1). For example, energy consultants are normally involved in the pre-retrofit survey and energy performance assessment phase, whereas designers and contractors participate in the project at the design and implementation phases.

Owners and tenants play important roles in making green retrofit decisions, particularly at the very early stage, namely, initial intention or setup phase (Liang et al., 2015). In this phase, normally only the owners and tenants, who propose preliminary retrofit plans and exchange opinions regarding retrofit, are involved. These stakeholders can decide whether to launch a retrofit project and continue to the next steps of energy audit, design, and implementation. The important role of owners in green retrofit is naturally and easily understood, whereas the role of tenants is often underestimated (Karvonen, 2013). Juan et al. (2009) indicated that the influence of tenants makes retrofit more difficult and risky than new buildings, because the cooperation and participation of tenants are required in an existing building retrofit (Miller and Buys, 2008). In new buildings, the clients, who will become the building owners after construction, can decide by themselves, whereas in retrofit, the owners have to consider the tenants because of their lease contracts. The satisfaction of tenants can directly influence the occupancy rate, rent, and owner reputation in the future. In addition to economic influence, the actions of tenants are identified as major determinants of energy consumption (Azar and Menassa, 2012b; Azar and Menassa, 2014). Tenants can affect the energy consumption difference by up to 100% through different behaviors, such as ventilation habits, indoor temperature setting behavior, and after-hour lighting use (Ürge-Vorsatz et al., 2009). Consequently, tenants are also essential stakeholders in green retrofit projects. Numerous owners and tenants intend to carry out green retrofit, but most of them are interrupted at the beginning because a consensus cannot be reached.

Conventional studies related to stakeholder analysis in green retrofit mainly focused on the owners and designers involved in the energy assessment and design phase (Ali et al., 2008; Stiess and Dunkelberg, 2013). However, a few recent studies have examined the tenants of existing buildings and their relationship with owners. Stephan and Menassa (2013) proposed an agent-based model to analyze the social network interactions among the stakeholders (i.e., owner, tenant, architect, and contractor) of commercial buildings. In their subsequent study, Stephan and Menassa (2014) emphasized that the network structure and confidence level of stakeholders can significantly influence their own alignment toward a unified retrofit objective. This agent-based model originally simulated the dynamic opinions of stakeholders who were influenced by their interactions to allow the adjustment of their values on three dimensions (i.e., cost, energy, and comfort) to an optimal retrofit decision. Fuerst and McAllister (2011) analyzed the rent, cost, and price of the buildings influenced by green retrofit and attempted to define an appropriate compensation to satisfy both owners and tenants.

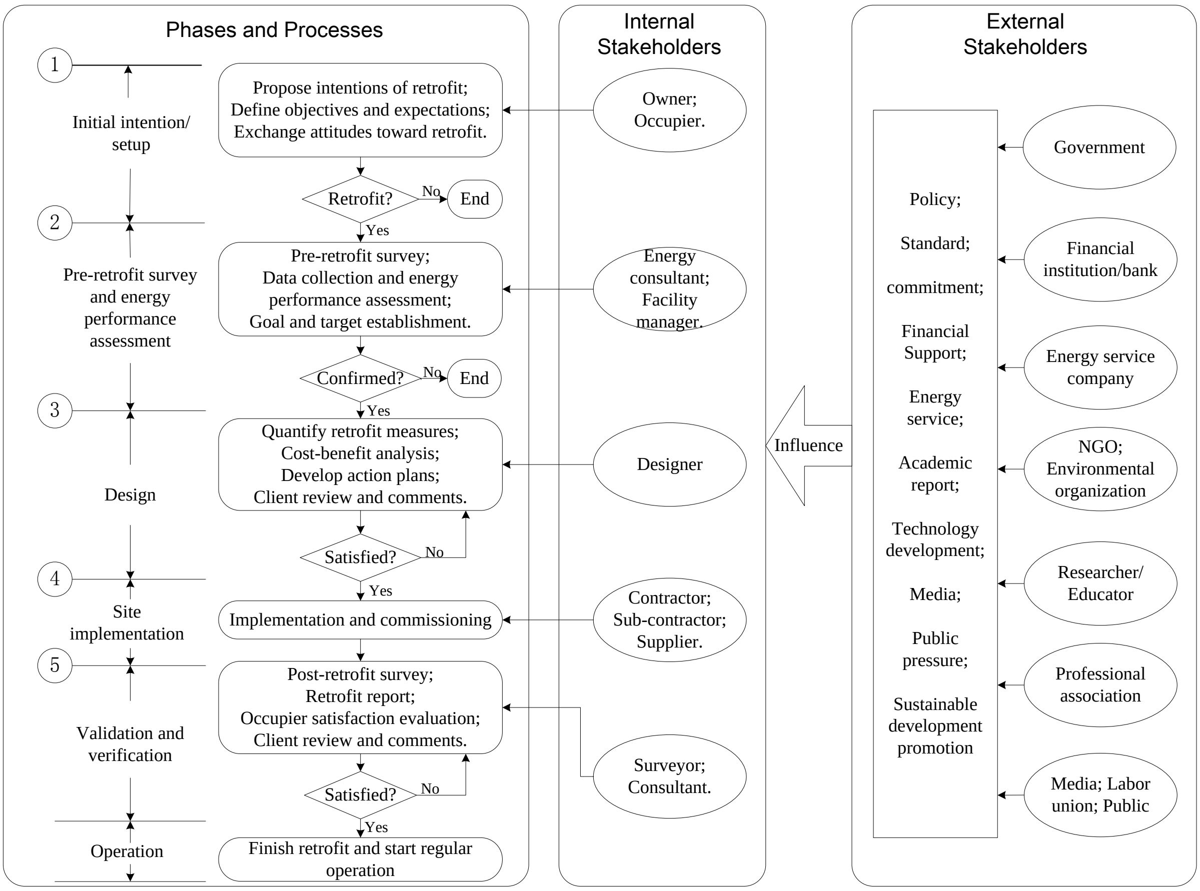


Figure 2.1 Phases and involved stakeholders in green retrofit projects

2.3 Occupancy Types

Unlike in new buildings, tenants are main stakeholders in green retrofit buildings. According to the occupancy type, existing buildings can be classified in three categories: owner-occupied, single-occupied (not by owner), and multi-occupied (Rhoads, 2010) buildings. Owner-occupied buildings are occupied by the owner rather than rented out, and thus owners of this building type can make decisions completely by themselves. Single-occupied buildings are rented to a single tenant, who is probably a company or institute in a relatively large scale. Given the single tenant's large scale and significant influence on the owner's profit, he has relatively high negotiation capabilities with the owner.

This single tenant has to agree to the retrofit decision, otherwise the plan will be difficult to implement. Multi-occupied buildings are occupied by numerous tenants, who are commonly in small scale. Every tenant only rents a small part of the building, and the rent from an individual tenant is not high enough to significantly influence the owner's profit. The owner has the dominant position in decision making, and if the small tenants do not agree with the owner, they can only choose to vote with their feet, that is, to terminate their contracts and move out.

Fuerst and McAllister (2011) stated that tenants are willing to compensate owners for the additional costs of green retrofit through higher rents. Miller and Buys (2008) argued that sustainable development is a non-negotiable criterion in building selection for the government and larger private organizations, whereas smaller organizations consider location and cost as the most dominant factors in building selection, although they view sustainability as an emerging consideration. In addition, for many tenants, sustainability in buildings is a relatively abstract concept. Small tenants in particular are relatively unaware and uninterested in cost-sharing arrangements and partnerships in green retrofit, which are perceived to be too complicated (Miller and Buys, 2008). In general, small tenants desire low cost, including rent and energy cost, whereas large tenants pursue more sustainability besides cost.

2.4 Drivers and Barriers of Green Retrofit

2.4.1 Drivers of green retrofit

Green retrofit is fragmented because the incentives and motives of stakeholders are not aligned. The main incentives of owners and tenants are identified through literature review and structured interviews with experts experienced in green retrofit projects. The incentives, which can be defined as the potential profits of green retrofit, can be classified into three categories: 1) direct incentives in short term, 2) direct incentives in long term, and 3) indirect incentives. The first category refers to incentives related to the economic benefits that can be reaped in a short time, such as higher rent, lower maintenance cost, and tax reduction. The second one also refers to economic benefits but in the long term, such as higher occupancy rate, rise in asset value, and longevity). The last category includes other incentives related to social and environment influences rather than economic interests. The incentives of owners and tenants are different, as illustrated in Table 2.1.

The principal drivers for the decision to retrofit a building are still primarily motivated to enhance their reputation, pursue higher rental values, improve the building quality, and attract new tenants, rather than to reduce carbon emissions or energy consumption (Carbon Trust, 2008). On the other hand, tenants, especially small tenants, are also profit driven (Rhoads, 2010). Thus, the strategies of owners and tenants should lean toward direct incentives, which means the priority should be direct incentives in short term above direct incentives in long term and followed by indirect incentives.

Table 2.1 Incentives of owners and tenants in green retrofit

Stakeholders	Direct incentives in short term	Direct incentives in long term	Indirect incentives
Owners	✓ Higher rent (Fuerst and McAllister, 2011; Thomas, 2010) ✓ Lower maintenance cost (Alanne, 2004; Lapinski et al., 2006; Ouyang et al., 2011; Rey, 2004) ✓ Subsidies/tax reduction (Fuerst and McAllister, 2011; Ouyang et al., 2011) ✓ Return on investment (ROI) (Entrop et al., 2010; Kaklauskas et al., 2004; Miller and Buys, 2008)	✓ Higher occupancy rate (Fuerst and McAllister, 2011; Ma et al., 2012; Thomas, 2010) ✓ Risk reduction (avoid premature obsolescence, increase in energy cost) (Fuerst and McAllister, 2011) ✓ Longevity (Kaklauskas et al., 2004; Mickaityte et al., 2008) ✓ Rise in asset value (Miller and Buys, 2008)	✓ Reputation enhancement (Gucyeter and Gunaydin, 2012) ✓ Social responsibility (Davies and Osmani, 2011) ✓ Tenants' satisfaction (Thomas, 2010; Xu et al., 2011)
Tenants	✓ Lower cost, including rent and energy cost (Caccavelli and Gugerli, 2002; Juan et al., 2010; Newsham et al., 2009; Rey, 2004)	✓ Productivity improvement (Fuerst and McAllister, 2011; Lapinski et al., 2006; Thomas, 2010; Xu et al., 2011)	✓ Comfort enhancement (Wang et al., 2010; Xu et al., 2011) ✓ Social responsibility (Davies and Osmani, 2011)

2.4.2 Barriers of green retrofit

Besides the aforementioned split incentives, there are other barriers that adversely impact the decision making on green retrofit, including costs or potential resistances. Similar to incentives, the main barriers of owners and tenants are also identified through literature review and structured interviews. The barriers are classified into two categories: 1) direct/economic barriers and 2) indirect barriers. The former category refers to barriers related directly to economic problems, such as high retrofit cost, finite capital, and long payback periods. The latter refers to other barriers not related directly to the economics, such as highly complex design analysis and solution and lack of building information. The specific barriers of owners and tenants are shown in Table 2.2. Similar to incentives, the weight of direct barriers should be heavier than the weight of the other barriers for both owners and tenants.

Table 2.2 Barriers of owners and tenants in green retrofit

Stakeholders	Direct/economic barriers	Indirect barriers
Owners	✓ High retrofit cost (Lapinski et al., 2006; Menassa, 2011; Xu et al., 2011) ✓ Long payback periods (Kasivisvanathan et al., 2012; Menassa, 2011) ✓ Finite capital (Davies and Osmani, 2011; Kasivisvanathan et al., 2012; Menassa, 2011; Stiess and Dunkelberg, 2013)	✓ Highly complex design analysis and solution (Davies and Osmani, 2011; Kasivisvanathan et al., 2012; Lapinski et al., 2006) ✓ Lack of building information (Davies and Osmani, 2011; Kasivisvanathan et al., 2012; Menassa, 2011) ✓ Lack of retrofit experience (Ali et al., 2008; Korkmaz et al., 2010)
Tenants	✓ Higher rent (Fuerst and McAllister, 2011; Thomas, 2010) ✓ Interruptions in operations (Kasivisvanathan et al., 2012; Miller and Buys, 2008) ✓ Risk in potential benefits of retrofits (energy may not be saved by retrofit) (Menassa, 2011)	✓ Lack of understanding or interest about the environment (Davies and Osmani, 2011) ✓ Lack of information (Davies and Osmani, 2011; Kasivisvanathan et al., 2012; Menassa, 2011)

2.5 Summary of the Chapter

This chapter first reviewed the stakeholders in green retrofit and their characteristics. The focus of concern was on the influence on green retrofit decision making and the phases involved in such process. The occupancy types were also summarized, and their influences on decision making were specified. Finally, the drivers and barriers of green retrofit were identified.

Chapter 3 Literature Review: Multi-Agent Systems

3.1 Introduction

MASs have rapidly developed in recent years because of the emergence of algorithms, approaches and technologies to support and improve agent-based systems. A MAS includes intelligent agents that can represent real-world objects (e.g. humans, vehicles and facilities) that follow different behavior criteria without global control, knowledge, and objectives (Ren and Anumba, 2004). An individual agent has incomplete resources, information, and capabilities to solve a global problem. Each agent only attempts to maximize its utility by cooperating with other agents. According to the characteristics of agents, MASs are essentially suitable for solving various complex, distributed, and dynamic problems. Therefore, they are appropriate to be adopted in the construction industry.

This chapter reviews recent literature about the MAS, with special focus on the issues in the construction industry. Then the advantages and disadvantages of the MAS are discussed, and the related applications are summarized. Finally, the development and prospects of the MAS are illustrated at the end of the chapter.

3.2 Key Issues of the MAS in Construction

The key issues of the MAS were first posed by Bond and Gasser (1988); since then, Sycara (1998) and other researchers have added to the issues and made improvements to them. Previous research suggests that reaching a stable state of coherent collective behavior in the MAS is a major challenge (Christodoulou, 2009). This challenge is also termed a “consensus” problem (Olfati-Saber et al., 2007). In most MASs, groups of agents need to reach an agreement over a variety of interests and make common decisions in relation to a number of problems (Olfati-Saber and Murray, 2004). However, as agents are autonomous and often lack the global perspective and information to reach a consensus automatically, relevant algorithms and mechanisms are needed to assist the process.

On the basis of previous work (Sycara, 1998), the main issues derived from the consensus problems in MASs can be classified into seven dimensions: (1) individual agent reasoning, (2) planning and scheduling, (3) organization, (4) resolving conflicts and negotiation, (5) resource and task assignment, (6) communication management, (7) adaption and learning. These dimensional problems can be categorized into three agent behavioral attributes, as shown in Figure 3.1. The research questions for each issue are illustrated in Table 3.1.

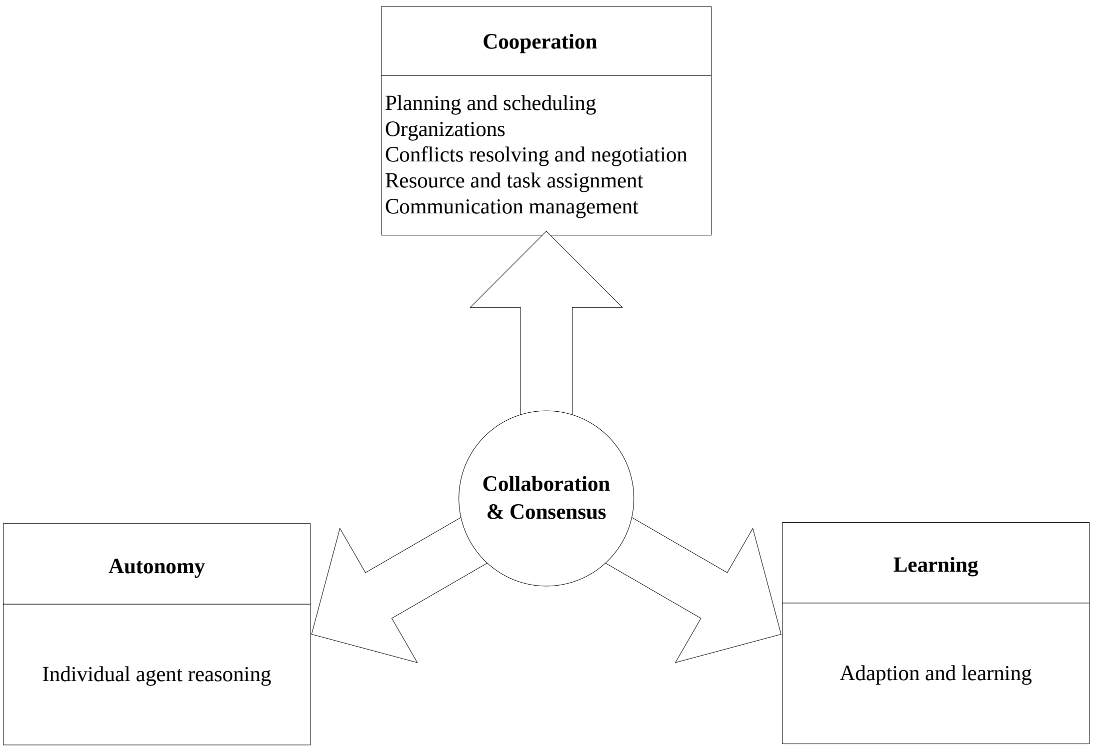


Figure 3.1 Main issues derived from the collaboration and consensus in the MAS

Table 3.1 Research questions of the main issues in collaboration and consensus

Attributes	Key Issues	Research Questions
Autonomy	agent reasoning	How do we enable agents to reason about their own actions and other agents' actions? How do we train agents to deduce results and optimize their own benefits?
Cooperation	planning and scheduling	How do we enable individual agents to plan based on incomplete information? How can the plans of individual agents be merged into a global plan? How can the agents adjust their schedule dynamically and efficiently?
	organization	How do we organize the agents appropriately? What relationship among agents is most efficient in the specific situation?
	conflicts resolving and negotiation	How do we recognize and resolve conflicts among a collection of agents? How can we attain a win-win solution from negotiations? How can the negotiation processes be simplified in order to save time, human resources, and cost?
	resource and task assignment	How do we decompose, describe, and assign tasks to agents? How can conflicts among different tasks be avoided? How can we make the task allocation more flexible to match the changes in projects? How do we manage limited resources in the MAS? How do we define the constraints and utilities of resources? How do we develop a mechanism that can allocate resources and maximize efficiency?
	communication management	How do we enable agents to communicate with each other? What protocols do we use to communicate? What information can they exchange and what is confidential? How can trust be built during communication?
Learning	adaption and learning	How do we enable agents to adapt to the environment? What should agents learn from their own experiences, other agent's experiences, and the environment? How do we improve agents' behavior in light of what they have learned? How do we enable agents to positively influence the behavior of other agents?

3.2.1 Issues on autonomy and individual agent reasoning

Individual agent reasoning is important to consensus of MAS because it enables agents to rationalize the behavior of others and avoid potential conflicts. Many studies on MASs have attempted to formalize a logical architecture for the sophisticated reasoning of agents. Studies tend to focus on specific aspects of agent reasoning, such as diagnostics and error recovery, which are considered critical in MASs. Odrey and Mejia (2003) developed a multi-level, multi-layer hierarchy to recognize and recover error, including a production module and an error recovery module along with a mediator module connecting them. According to this architecture, agents have responsive and adaptive capabilities for self-adjustment. Another aspect is risk and contingency management. MASs can manage contingency by adopting game theory to improve reasoning (Sheremetov et al., 2004).

In the construction domain, Rojas and Mukherjee (2006) suggested a general purpose situational simulation framework involving an understanding that reasoning processes can be isolated using a conceptual classification of problems in construction management. This "general purpose multi-agent framework" of agent reasoning is composed of some basic modules (operations), which are used to exchange information and act with a specific operator. The simulation platform based on this framework can reflect realistic situations and improve the construction management process.

3.2.2 Cooperation issues

Planning and schedule

The MAS is recognized as an effective way to realize planning and scheduling (Phanden et al., 2011), as well as a tool for agents to improve coherence by planning their actions (Sycara, 1998). The scheduling problem that widely exists in construction is typically considered to be an NP-hard problem (Pinedo, 2012), because finding an optimal solution for it is impossible unless an enumerative algorithm is utilized. This problem requires polynomial computation time, which increases exponentially. Compared with traditional approaches, agent-based approaches have several advantages for scheduling: parallel computation with high efficiency, easy-to-realize dynamic scheduling, and robustness with fault tolerance (Shen et al., 2006b). An agent-based scheduling analyzed from those three perspectives is presented in the following.

The MAS can improve scheduling efficiency because it can divide a complex problem into smaller units that can be operated by each agent concurrently. Agent-based scheduling is a conceptual framework that must be associated with a certain algorithm to solve a specific problem. Ant colony algorithm is one of the common algorithms applied in agent-based scheduling, which has attracted numerous studies (Mullen et al., 2009; Shyu et al., 2006).

MASs can also be used in some traditional scheduling methods to improve efficiency. Research attempts to use the MAS were conducted recently to improve the Petri net, which is widely used in process modeling (Molinero and Nunez, 2011; Stuit and Szirbik, 2009). As the MAS is naturally distributed, it is also suitable for modern information technologies, such as the Internet, distributed computations, and cloud framework (Singh and Malhotra, 2012). Yen (2002) introduced an agent-based communication infrastructure to handle different scheduling systems on the Internet. The infrastructure is very similar to the scheduling situation in construction, where agencies, contractors, and subcontractors schedule separately and then negotiate to combine their schedules.

Dynamic adaption is another advantage of agent scheduling. Most construction projects are in a dynamic environment, where tasks, designs, and resources change and other unpredictable events often happen during the implementation of a project. Thus, dynamic scheduling is important in the real world, especially in construction. Ouelhadj and Petrovic (2009) compared several algorithms of dynamic scheduling, including heuristics, meta-heuristics, MAS, and other artificial intelligence (AI) algorithms. "The comparative study provided evidence that MASs are a very promising area of current and future research in dynamic scheduling" (Boecker et al., 2009).

Hong et al. (2009) proposed a context-aware system for personalized scheduling according to the user's profile. The system will provide users with a dynamic plan based on different user profiles, different input, and different environment input. Kim and Kim (2010) developed an agent-based system to evaluate congested flows of equipment and make dynamic plans in real time during the execution of a construction project. The system requires high real-time, dynamic, and predicable abilities because the traffic of equipment constantly changes.

Apart from traditional algorithms, such as genetic algorithm, ant colony algorithm, particle swarm optimization, and CPM, some novel algorithms have recently emerged from other disciplines (Kim and Paulson, 2003; Taghaddos et al., 2012). Kim and Paulson (2003) developed a new economics-inspired approach, which adopts a common conception used in welfare economics known as “compensatory.” Taghaddos et al. (2012) developed a new model, inspired by “persistence of vision,” which divides a scheduling problem into smaller resource allocation problems at points in time, and then solves each resource allocation problem by auction. In construction projects, knowing the exact time of each task is difficult, and so delays and being ahead of schedule are quite common. To avoid crashing cost, time, human resources, or facilities (Hall, 2012), a robust schedule must be created.

Organizations

Organizations are generally considered as structures of information and control relations existing among agents, and these structures provide a high-level view of cooperative problem solving (Sycara, 1998). Horling and Lesser (2004) surveyed the organization of the MAS and found 10 types of organizational structures: (1) hierarchy, (2) holarchy, (3) coalition, (4) marketplace, (5) congregation, (6) society, (7) federation, (8) matrix, (9) team, and (10) compound organization. No one organization structure is better than the others because each type has advantages and disadvantages. Wilhite and Fong (2012) summarized the organization of the MAS to six network categories: (1) line, (2) tree, (3) grid, (4) random, (5) complete, and (6) scale-free. On the basis of the hypothesis analysis, the authors found that an organization’s structure influences not only cooperation but also innovation in construction.

Other studies have considered the organization of the MAS for specific applications. Kim and Russell (2003) used two organizational structures for the MAS to coordinate an earthwork system, namely, a vertical relationship and a horizontal relationship, which were found to be highly reactive and flexible. Son and Rojas (2011) introduced an organization framework for temporal team collaboration in large-scale construction projects, and proposed an approach to examine organizational issues. The framework also indicates how individual effort influences the system's efficiency: the more effort needed to build relationships, the less the efficiency in the network.

Resolving conflicts and negotiation

Negotiation is a key factor of MAS consensus. Xue et al. (2005) suggested that the relationship between negotiation and consensus is such that negotiation is the decision-making process necessary to reach a consensus by searching for a solution space. In other words, multi-agent negotiation is considered a helpful tool to resolve conflicts and balance profits among participants (Duan et al., 2012). From another perspective, Rosenschein (1994) divided negotiation into task-oriented, state-oriented, and worth-oriented domains. Dzeng and Lin (2004) classified negotiation issues based on the optional range, which include price, limited options, quantitative options, and qualitative options. A model was developed for each category to illustrate how they influence negotiation.

Lee (2004) found that communication between agents and concession strategies are the two main factors of automated negotiation in the MAS. The former defines languages and protocols for exchanging messages, and the latter defines the mechanism to execute the negotiation process. Wooldridge and Jennings (1999) defined negotiation protocol as a set of rules to manage interactions, including types of participants, states, events, and actions. The mainly used protocols are contract net protocol, monotonic concession protocol, and fish market protocol, which are suitable for one-to-many, one-to-one, and many-to-many participants, respectively (Liao et al., 2013).

The agent-based algorithms used to improve negotiations can be categorized as either game-theoretic techniques, physics models, operation research models, or informal models (Kraus, 1997). Ren et al. (2003c) categorized negotiation theories into game theory, economic theory, and behavior theory, all of which inevitably overlap. Similarly, Anumba et al. (2003) suggested two categories: game theory and behavior theory. However, regardless of the category, the algorithms are typically used for saving time/cost, aiding decisions, and optimizing negotiation results (Liao et al., 2013).

The aim of negotiations is to reach “Pareto optimality,” which is the maximum utility (Yager, 2002). Various mechanisms are designed to realize this aim, with game theory one of the most commonly used methods to find strategies satisfying the joint requirements of participants after conflict and competition (Ren et al., 2003b). An approach for negotiating construction claims has been proposed in several studies (Ren et al., 2003a; Ren and Anumba, 2002; Ren et al., 2002). Ren et al. (2003b) and Murray (2003) defined a concession mechanism with the principle of conflict avoidance, wherein the negotiation will terminate if the risks of conflict for each side are zero. Ren and Anumba (2002) opined that although scholars may claim Nash equilibrium to be an optimal solution, it is actually based on complete information that is not available in real-world situations. Ren et al. (2002) evaluated this approach as good in terms of efficiency, simplicity, and stability.

Although game theory is suitable for problems with agents in small number, when the number of agents become large, game-theoretic methods consume too much time (Kraus, 1997). Some algorithms for large-scale agents have emerged because of this disadvantage. Kim et al. (2003) introduced a bidding mechanism that can be built among subcontractors to trade utilities, where they can compensate each other for agreeing to changes in the schedule. This mutually beneficial arrangement is known as “Pareto improvement” and is especially effective in mega projects. El-Adaway and Kandil (2010) suggested an approach that judges the category to which a new case belongs, so that if the negotiator can prove the new case is similar to a past one, it can be treated in the same way.

To evaluate attributes quantitatively, Xue et al. (2005) proposed an approach that uses an $m \times n$ evaluation matrix to illustrate *m* participants and *n* attributes. This kind of evaluation can help participants clarify the advantages of the plans and make precise decisions during negotiations. Xue et al. (2009) improved their algorithm by using a novel approach: a relative entropy method. This method was based on the information entropy model that quantitatively evaluates the preference of negotiators for various attributes. An agent-based negotiation platform has been developed to realize this approach (Xue and Ren, 2009), which is essentially a complete information algorithm. Complete information algorithms represent the third party, such as coordinators, who need to know all the users’ preferences, even that which is confidential. Some algorithms represent one of the participants only and do not know the information of others involved (Lee, 2004).

Resource and task allocation

Task and resource allocation are correlative, which means specific responsibilities and resources are assigned to multiple agents.

Task allocation is often associated with collaborative and distributed design, a complex activity requiring good communication among teams with different backgrounds. (Chu et al., 2009) investigated the interaction among works and developed a type of MAS to realize collaborative 3D design in construction projects. The system includes server agents and client agents, both of whom are assigned specific tasks and work separately with their technologies. Watkins et al. (2009) developed an agent-based “bottom-top” approach that defines the efficiency of every labor activity so that task allocation can be planned more accurately.

Resource management includes money, human resources, facilities, information, and knowledge management. Traditionally, most research in the construction domain focused on tangible objects, such as money and facilities. However, intangible objects have attracted increased attention recently, especially those related to information and knowledge (Wu, 2001). Given the fragmented nature and subjectivity of construction data structures, the majority of experiential information, knowledge, and memory are stored only in human minds. However, the developing complexities of projects demands more effective approaches to manage these subjective resources (El-Diraby and Zhang, 2006). (Koo et al., 2012) proposed an intelligent knowledge management system based on the MAS. The basic idea of the approach is integrating the individual agent knowledge management system to a union one. The system structure is based on independent agents and is thus loosely coupled, which means the system can be easily reconfigured over time as the environment changes.

Among the numerous approaches that have been developed for resource allocation, two have attracted greater attention than the others. One is based on operation techniques for scheduling, and the other one is a market-oriented approach. Shen et al. (2006b) suggested that scheduling and resource allocation are related to each other, such that resource allocation can be considered a note of schedule and schedule can be considered as several resource allocations on a timeline. With appropriate mechanisms requiring definition to reach consensus and utility maximization at the same time (Phelps et al., 2010), and thus some kind of bidding, compensation approaches have been proposed (Kim and Paulson, 2003; Kim et al., 2003; McKelvey et al., 2009; Ziogos and Tellidou, 2011).

Communication management

Agents can improve their consensuses by exchanging information (Sycara, 1998) and effective communication (Yen, 2002). Obonyo (2013) defined communication as speech actions whose meaning is described by agents. (Huang et al., 2006) developed a three-tier system for collaborative communication to increase system performance, security, and maintainability. Trust is a crucial subject in communication management, especially in the MAS, where agents work separately and the environment changes constantly. Tweedale and Cutler (2006) systematically reviewed trust in the MAS and classified it into categories to compare the advantages and disadvantages of the models.

Communication technology is another research direction of MAS communication management. Traditionally, the work culture of the construction domain depended on face-to-face communication. However, with recent technological advances, wireless and inter-operative communications have become commonplace. Aziz et al. (2006) reviewed intelligent wireless communication services in construction, including Wi-Fi, Bluetooth, and 3G. They compared these technologies and discussed how to integrate them with agent-based technologies to support mobile construction workers. Lee and Bernold (2008) developed a wireless system to realize "ubiquitous communications" that can link information islands. A platform prototype was used to alert outside workers about weather changes. Lu et al. (2011) observed that although radio frequency identification (RFID) technology has developed dramatically and is now widely used in various domains, such as retail, security, and transportation, it is not widespread in construction. They illustrated several scenarios in which RFID might be used, such as logistic and supply chain management, inventory management, quality assurance, access control and labor attendance records, tracking of machines and tools, and machine operations and records. Ren et al. (2011) developed an RFID system for material planning, ordering, receiving and storing, handling and distribution, and site usage and monitoring in construction projects. Cerovsek (2011) integrated RFID with building information modeling (BIM) to automatically generate models.

3.2.3 Adaptation and learning issues

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

Some studies have focused on the specific approaches and applications of agent-based learning. Bayesian learning is one of the most widely used approaches for updating strategy after learning from previous experience. Some researchers have used it in negotiations (Anumba et al., 2003; Ren and Anumba, 2002; Ren et al., 2002, 2003c), in contract systems (Montano et al., 2008), and in supply chain management (Xue et al., 2009). Agent-based learning has been adopted in some new areas in the construction domain. Azar and Menassa (2012a) introduced an agent-based novel learning approach for building energy performance. The agents of this system can record and learn the energy performance of individuals, and then use the results to give suggestions on how to save energy.

3.3 Advantages and Disadvantages of MASs

One advantage of MASs is their ability to act separately from various components of the engineering or business processes, which are executed by a number of agents. MASs are suitable for a sophisticated pattern of interactions, such as cooperation, coordination, and consensus (Ren and Anumba, 2004). In addition, MASs are robust because they do not rely on a centralized control center. Hence, the loss of one agent will not panic the system. Similarly, MASs can break down a problem into small pieces that can be assigned to different agents for parallel processing (Shen et al., 2006b). These abilities of MASs are suitable for dealing with problems that are:

(1) Too large to be solved by a single agent because of limited time or resources. One of these problems is the resource-constrained scheduling problem, which is a time-consuming NP-hard optimization problem (Taghaddos et al., 2012).

(2) Inherently distributed, but require collaboration and interaction (Sycara, 1998). For example, the collaborative design by individual team members (Anumba et al., 2002; Chu et al., 2009; Ren et al., 2011) and the control of a distributed sensor network in construction fields (Dibley et al., 2011; Wu et al., 2010).

(3) Related to the self-interest of the participants. In the real world, most construction participants are autonomous and want to maximize their own profit. Agents can simulate negotiations, arguments, and conflicts among stakeholders and efficiently find an optimal solution (Anumba et al., 2003; Dzeng and Lin, 2004; Kraus, 1997; Ren et al., 2003c; Xue et al., 2009).

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

The application of MASs in construction can potentially improve the process of dealing with decentralized, complex, and dynamic problems to achieve better efficiency, quality, and cost. However, the disadvantages of MASs have prevented their significant development. The fundamental disadvantage of MASs is the ongoing debate between the research communities in the areas of software engineering and AI (Dimou et al., 2009), leading to sluggish software development. Without the support of a practical toolkit for real applications, MASs are more similar to theoretical models on paper rather than to simple systems. The lack of a systematic methodology or a clear handbook that allows people to model their applications from MASs also hinders their development because construction problems are too complex to handle without an appropriate guide.

3.4 Applications

MASs, which emerged from AI, have been widely used in many other areas, such as manufacturing, transportation, information and communication, and space technology. In the construction domain, MASs have rapidly developed and have been used in almost all aspects of the construction process. The applications of MASs in previous studies are listed in Table 3.2.

Table 3.2 Applications of MASs identified by previous research

Phases	Applications	Description of topics	References
Design	Decision support system	Agent-based model for collaborative design	(Anumba et al., 2003; Anumba et al., 2002; Du and El-Gafy, 2012; Ren et al., 2013; Ren et al., 2011; Wang et al., 2010; Xue and Ren, 2009; Yan-chuen and Gilleard, 2000; Zhang et al., 2005)
	Evaluation and demand analysis	Analysis of stakeholders and their demand	(Andrews et al., 2011; Azar and Menassa, 2010; Azar and Menassa, 2012a; Kashif et al., 2011; Koo et al., 2012; Zhang et al., 2010)
	Computer-aided design	Collaborative 3D design model	(Chu et al., 2009)
Construction	Procurement management	Agent-based software for supply chain	(Fox et al., 2000; Jiao et al., 2006; Kwon et al., 2011; Ng and Li, 2006)
		Agent-based modeling and simulation	(Min and Bjomsson, 2008; Soroor et al., 2012; Tah, 2005; Xue et al., 2011)
	Negotiation	Framework for MAS negotiation	(Xue et al., 2005)
		Simulation and platform of negotiation	(Dzeng and Lin, 2004; Luo et al., 2002; Ren et al., 2003a; Ren et al., 2002, 2003b, c; Unsal and Taylor, 2011; Xue and Ren, 2009; Xue et al., 2009)
	Scheduling	Integration of schedules from various participants	(Christodoulou, 2009; Watkins et al., 2009)
		Adaption to the dynamic environment	(Christodoulou, 2009; Interrante and Rochowiak, 1994; Karageorgos et al., 2003; Kim and Paulson, 2003; Kim et al., 2003; Molinero and Nunez, 2011; Ouelhadj and Petrovic, 2009)
	Dispute resolution	Methods in claim and compensation	(El-Adaway and Kandil, 2010; Kim and Paulson, 2003; Kim et al., 2003; Ren et al., 2003a; Ren et al., 2002, 2003b, c)
	Site management	Simulation of construction site	(Aziz et al., 2006; Du and El-Gafy, 2012; Kim and Kim, 2010; Lee and Bernold, 2008; Watkins et al., 2009)
Operation	Maintenance	Materials and facilities management	(Bernhardt and McNeil, 2008; Osman, 2012; Shen et al., 2012)
Others	Knowledge management	Information and knowledge management	(El-Diraby and Zhang, 2006; Obonyo, 2013)
	Education	Virtual coaching and education	(Rojas and Mukherjee, 2006)

Although most studies have focused on traditional areas, new applications have emerged that require more attention from researchers. The first among these new applications is BIM, which has drawn significant attention in recent years (Cerovsek, 2011; Volk et al., 2014). BIM is a collection of visualized building data, particularly in 3D modeling. However, BIM primarily models the objects of a building without human behavior (Porter et al., 2014), which may significantly affect the building during its whole life cycle, from design and construction to operation and retrofit. The integration of the MAS and BIM can improve the performance of BIM, considering that the MAS can simulate human behavior in buildings and analyze the interaction of human and buildings in a virtual environment modeled by BIM. Porter et al. (2014) proposed an application of the MAS in performing dynamic security analysis in a BIM environment to simulate the human behavior of attacking and defending facilities in buildings. Cambeiro et al. (2014) developed an application for multidisciplinary, integrated, and collaborative work among agents to integrate all agents in different phases with the MAS, which was supported by BIM. Other potential applications of the MAS integrated with BIM have also been reported, such as collaborative design (Durif et al., 2013) and occupants' energy consumption (Azar and Menassa, 2012a; Jahn et al., 2012). On the basis of previous studies, MAS-assisted BIM can develop more realistic models and perform more accurate analysis.

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

Finally, MASs have been applied in applications related to sustainable development, such as carbon emission, energy performance, green building, and green retrofit (Azar and Menassa, 2010; Zhang et al., 2010). Building occupants can affect the results of building energy consumption simulation by more than 150% when they have different energy consumption behaviors (Clevenger and Haymaker, 2006). Although the occupants may have a significant influence on energy consumption levels, actual energy simulation software do not consider factors related to occupancy (Hoes et al., 2009). However, the MAS could can assist in simulating the energy consumption characteristics of the occupants to enhance the performance of traditional software (Azar and Menassa, 2010; Kashif et al., 2011). From the perspective of design and construction, green building and green retrofit involve various stakeholders with different disciplinary backgrounds, as well as complex environmental constraints (Ma et al., 2012). The MAS can simulate stakeholder characteristics and behaviors under specific constraints in building energy saving design and implementation (Zhang et al., 2010) .

3.5 Development and Prospects

The process of developing solutions for theoretical and practical problems in the construction domain is illustrated in Figure 3.2. The process is iterative (Ren and Anumba, 2004). First, specific industry problems should be identified and divided into sub-problems (e.g., stakeholders, procedures). MASs are then modeled by abstracting characteristics, defining constrains, quantifying, and mapping the model. After modeling, algorithms and mechanisms should be developed to address the problem. MASs are then implemented by appropriate software and platforms. The specific problems should be resolved based on the MASs. Nevertheless, new problems may emerge after validation and evaluation. Thus, the development process should be run again to develop MASs that are more adaptive to real situations. The key issues of the MAS identified by this study can offer solutions and contributions to every step of the process. Outside the internal iterative development process, external areas (i.e., theoretical model of the MAS, development trends of construction, and advanced applications of the MAS in other domains) can also improve the process.

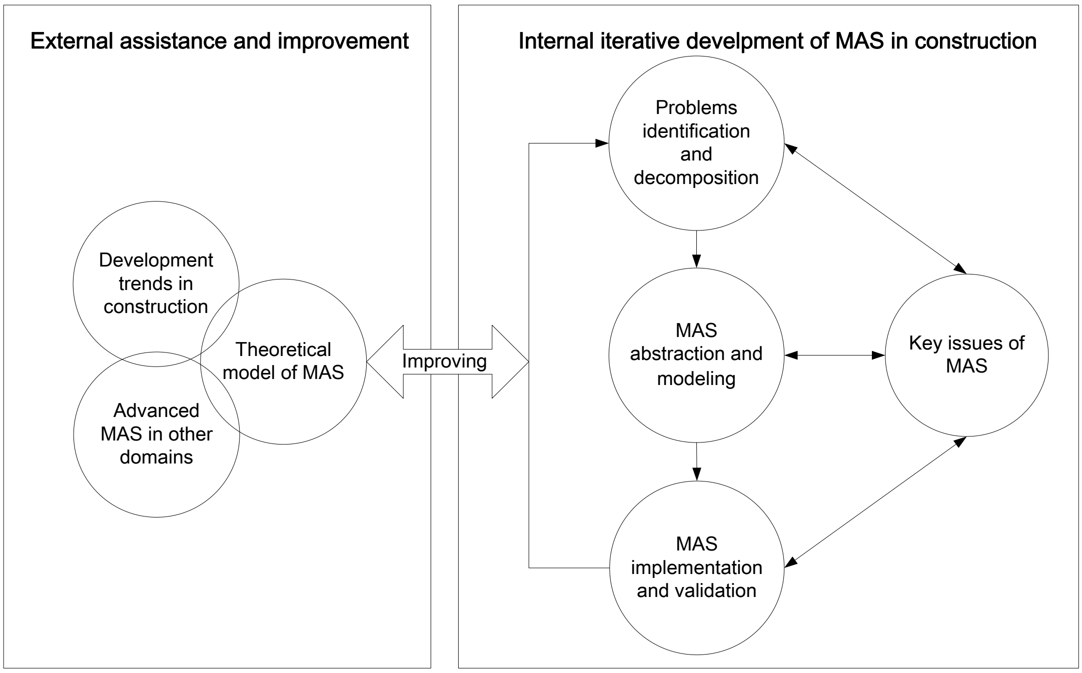


Figure 3.2 Development process of the MAS in construction

On the basis of the development process, numerous new approaches have emerged and technologies have been continuously updated. In the future, the following directions may require further attention.

System robustness under uncertainty: Construction projects often have tight deadlines, budgets, and resource constraints. Thus, traditional approaches may crash when changes are applied. MASs are suitable for this condition because of their ability to adapt easily to new situations. Despite being dynamic, MASs, however, are not designed for uncertainty. Future MASs should focus more on uncertainties when simulating the environment and human behavior, including the stochastic process or other probability distributions.

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

Integration with modern algorithms and approaches: The MAS is a type of framework that has been previously integrated with game theory, Bayesian learning, genetic algorithm, and ant colony algorithm. However, in the previous decade, several agent-related algorithms and approaches have been developed, some of which are now widely used, but not in the field of construction. For example, the Laplacian-based consensus algorithm has recently been developed and used in various areas. However, in the construction domain, few studies have employed this framework. Therefore, modern approaches should be followed and adopted in this field.

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

3.6 Summary of the Chapter

"Collaboration and consensus" was identified as the key success factor in construction, where fragmentation is a serious problem. However, this success factor is difficult to attain because of inherently distributed problems, self-interested participants, and the dynamic environment in construction. MASs are naturally suited to support such problems because of the autonomous, cooperative, and learning behavioral attributes of agents.

Seven key issues of collaboration and consensus were identified in this chapter, some of which had to be emphasized. Negotiation is an essential process to consensus because the initial states of agents should be different. New mechanisms of negotiations were developed by previous researchers, among which game and behavior theories were widely used. Planning and scheduling could improve agent coherence from another perspective. The MAS can support schedules with its parallel processing ability and adaption to dynamic changes. Similarly, resource and task allocation is a key issue in collaboration. Appropriately assigning resources and tasks to agents could enhance efficiency and eliminate conflicts.

Scheduling, dispute resolution, and decision support system in collaborative design have attracted significant attention in previous studies. Aside from these traditional areas, new applications were suggested in this review, such as BIM, knowledge management, and sustainable development. The development process of MASs in the construction domain is iterative in three steps, namely, problem identification and composition, problem abstraction and modeling, and MAS implementation and validation.

Chapter 4 Research Methodology

4.1 Introduction

This chapter first presents the proposed research framework in this study. Scientific methodologies are then discussed from both qualitative and quantitative perspectives, followed by a detailed description of the research methods adopted to achieve the research objectives in this study.

4.2 Research Framework

Detailed analysis techniques and data analytical tools to achieve the research objectives are described in Table 4.1. This study used both empirical methods, including interviews and focus group meetings, and theoretical methods, including game theory and agent-based modelling.

Table 4.1 Research methods for research objectives

Research objectives	**Analysis methods**	**Analysis techniques**
(1) To analyze the relationship of stakeholders and their priorities in green retrofit through a two-mode social network analysis.	1. Document analysis 2. Interviews 3. Focus group meeting 4. Data analysis	1. Literature review 2. Content analysis 3. Statistical analysis 4. Social network analysis
(2) To build a model of decision-making behaviors based on game theory for optimizing decisions of key stakeholders on green retrofit	1. Document analysis 2. Data analysis	1. Literature review 2. Game theory
(3) To develop and validate an agent-based platform on the basis of the proposed model to support decision making on green retrofit.	1. Document analysis 2. Data analysis 3. Case study	1. Literature review 2. Agent-based modeling 3. Comparative analysis 4. Sensitivity analysis

4.3 Research Methods

To achieve the three research objectives, the following research methods are applied.

4.3.1 Document analysis

Document analysis is designed to resolve research problems and questions by investigating recorded information and published documents. The major sources of document analysis are various types of documentation. Document analysis is the major qualitative method for in-depth content analysis and review of existing data. In general, this method can be categorized into two approaches in detail based on the difference of data source, namely, content analysis and existing data analysis. Content analysis systematically reviews references from a theoretical perspective (Dane, 1990). In the present study, literature review is the major form of this analysis. Literature review is a method used to systematically understand existing knowledge, findings, theoretical contributions, and practical applications in a specific research field on the basis of secondary sources (Verd, 2004). The target documents for review include academic publications and other paper-based or web-based resources (Rowley and Slack, 2004). In this research, a comprehensive literature review of stakeholders in green retrofit and their relationship and decision-making behaviors was conducted. Research gaps and limitations were identified and summarized to establish the research objectives, which serve as solid reference foundations for the following analyses. Official publications and regulations issued by central, local, and national departments were reviewed to identify existing achievements in the current construction practice.

4.3.2 Interviews

A skillful interviewer can get ideas, probe responses, and explore the motives and feelings behind the respondents (Bell, 2010). Among all interview types, expert interview, in which experts in a specific field are the interviewees, is an effective way to capture professional information and comments. In the current research, experts refer to experienced green retrofit practitioners. Through expert interviews, the conceptual framework can be modified and refined. Four expert interviews were conducted with designers, contractors, clients, and facility managers. Interviewees provide experiences, comments, and suggestions on the design process, the decision-making criteria, and the relationship of stakeholders. In the future, more expert interviews can be conducted to collect suggestions for the framework.

4.3.3 Focus group meetings

Focus groups are helpful if an in-depth understanding of people's views on an issue is required. A focus group meeting aims to gather different people with a shared interest, concern, or experience in a specific issue, and then provide an environment for them to focus the discussion on this issue (Bell, 2010). This method will be used to test and evaluate the effectiveness of the proposed framework in this study. In the focus group meetings, professionals are invited to view the case study results, discuss the proposed approach, and give their feedback. Two focus group meetings have been conducted in Hong Kong and Beijing to obtain information about stakeholders and key success factors.

4.4 Data Analysis Techniques

4.4.1 Social network Analysis

The concept of SNA was developed from social network theory, which is an interdisciplinary endeavor derived from sociology and anthropology (Mitchell, 1969), and incorporates mathematical, statistical, and informational methodologies (Yang, 2014). “Social network” can be defined as “a specific set of linkages among a defined set of persons, with the additional property that the characteristics of these linkages as a whole may be used to interpret the social behavior of the persons involved” (Mitchell, 1969). Furthermore, Wasserman and Faust (1994) emphasized that the social network focuses on the links that tie each individual to other individuals. The classical one-mode social network refers to the set of actors and the links between them, which are the two essential elements in a social network (Yang, 2014).

In stakeholder analysis, the actors in any social network are defined as stakeholders, and the links are defined as the relationships among them. SNA in stakeholder analysis can provide a relationship structure of the stakeholders, a structure that is illustrated by a graph of the network. The nodes in the graph represent the stakeholders, and the links are the relationships among them. Additional information can be represented in the graph; for example, the shape of nodes representing the type of stakeholder, and the width or length of links representing the tightness of relationships. Some methods based on graph theory are also developed to improve the SNA of stakeholders.

SNA is a widely used method in stakeholder analysis. Through some analysis methods (e.g., structured interviews, workshops, snowball sampling, and questionnaire surveys), SNA can identify stakeholders, map their interrelationships, and analyze their priorities, influence, clusters, and other attributes. Prell et al. (2009) applied SNA to natural resource stakeholder analysis and determined that stakeholders play more central roles in the network of nature resource management. Yang (2014) identified the priority of stakeholders through SNA for a regional renewal project in Australia. However, most previous studies only focused on the relationship among stakeholders by using the one-mode network, rather than on the relationship between stakeholders and some essential factors in project management. Yang and Zou (2014) integrated stakeholder and risk analysis by SNA, which is called stakeholder-associated risk analysis. They proposed an SNA-based model to identify and analyze the interrelationships between stakeholders and risks in complex green building projects. However, their model still used the one-mode network, which was not very direct, and thus could not show directly the relationship of two sets. SNA can identify stakeholders, map their interrelationships, and analyze their priorities, influence, clusters, and other attributes. The stakeholders are connected with each other and they have interactions with each other. Therefore, it is appropriate to model their relationship with social network analysis.

Two-mode Network Models

A two-mode network is beneficial for modeling the relationship between two groups. Some two-mode network-based models have been proposed to analyze the relationship between individuals and their associated attributes, such as board members with the companies they lead (Robins and Alexander, 2004). A major difference of the two-mode network from the classical one-mode network is that the former's nodes are in two disjointed sets, and the links are between the nodes of both sets (Kim et al., 2013). That is, two nodes in the same set should not be linked.

A two-mode network can be represented as a triplet G = ($\bigtriangledown$, $\bigtriangleup$, E), where $\bigtriangledown$ is the set of top nodes, $\bigtriangleup$ is the set of bottom nodes, and E $\in \bigtriangledown \times \bigtriangleup$ is the set of links (Latapy et al., 2008). Figure 4.1 shows an example of one-mode network versus two-mode network. Nodes 1 to 3 in the two-mode network are the top nodes, and nodes A to E are the bottom nodes. No link exists between top nodes or between bottom nodes.

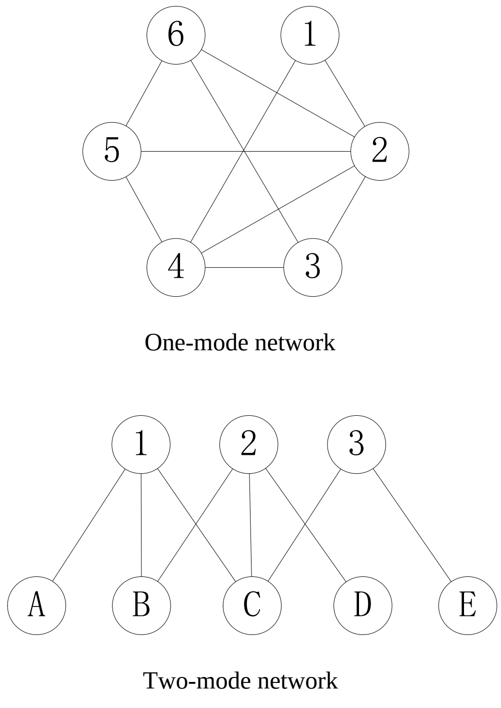


Figure 4.1 Example of one-mode network versus two-mode network

Analytical approaches used for two-mode networks

Although various methods and notions have been utilized to analyze the classical one-mode network, methods for analyzing two-mode networks have not yet been well developed (Latapy et al., 2008). Two typical approaches are used for two-mode networks. The first approach is a direct method, which analyzes the two-mode network directly (Everett and Borgatti, 2013). The second is a "conversion method," which converts a two-mode network into a one-mode network, so that it can be analyzed by methods defined for classical one-mode networks. The direct method has attracted attention in recent years, and some specific notions for two-mode networks have been proposed, but these often lack rigor and generality, making the relevance of the results difficult to evaluate (Latapy et al., 2008). Therefore, more studies on two-mode networks have used the conversion method. Some scholars assumed that the latter method significantly causes information loss, because information of the bipartite structure may disappear after transformation (Latapy et al., 2008). However, Everett and Borgatti (2013) argued that the conversion method can retain all the information of the original two-mode network in most empirical cases. Table 4.2 shows the categories of methods for two-mode networks.

Table 4.2 Categories of methods for two-mode networks

Methods for two-mode networks		**Advantages**	**Disadvantages**
Direct method	Some specific notions (e.g., bipartite statistics)	1) Directly handle two-mode networks 2) No information loss	1) Lack of rigor and generality 2) Results are difficult to evaluate

Conversion method	Projection	1) Can use methods for one-mode network 2) Results are easy to evaluate and compare	1) Information of the bipartite structure may be lost

Projection is used to project a two-mode network to a one-mode network. There are two types of projection: top projection and bottom projection. Top projection links two nodes in ▽ when they are linked to a common neighbor in △. This projection can be represented by G▽=(▽, E▽), where the value of E▽ is defined as the number of common neighbors in △ multiplied by the weighted value of links in E. The process of bottom projection is the same as that used in top projection. Several previous studies used projection to convert and analyze two-mode networks. For example, an actor-movie network was projected to a one-mode network of actors, where two actors were linked if they played in the same movie (Newman, 2001a).

We can apply the same approach for project management (PM) analysis to project a stakeholder–CSF two-mode network to a one-mode network of stakeholders. The tightness of relationships among stakeholders with regard to CSFs can be illustrated by this top projection, based on which stakeholders' influence on CSFs and the success of projects can be identified. An illustration of the projection for stakeholder–CSF analysis is shown in Table 4.3 and Figure 4.2. Table 4.3 shows an example of a stakeholder–CSF relationship matrix. In the matrix, stakeholders are coded with S# and CSFs are coded with C*, where # represents the identity of each stakeholder, and * is the identity of each CSF. A value of one at the cross point of S# and C* in the matrix indicates a link between them, and zero indicates that no link exists. The matrix of three stakeholders and five CSFs in Table 4.3 can be visualized to the network in the left side of Figure 4.2. In addition, the relationship of stakeholders through CSFs can be built by the top projection, as shown at the right side of Figure 4.2.

Table 4.3 Example of a “two-mode to one-mode projection” matrix

	C1	C2	C3	C4	C5
S1	1	1	1	0	0
S2	0	1	1	1	0
S3	0	0	1	0	1

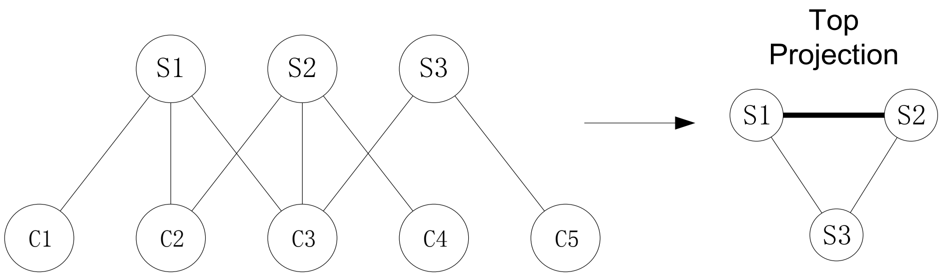


Figure 4.2 Example of a projection for the two-mode network analysis

4.4.2 Game theory

Game theory is used to model the decision behaviors of owners and tenants in green retrofit. Previous studies have determined that many owners and tenants intend to implement green retrofit, but only a few can reach a consensus and continue its implementation. Although other methods can be used to identify the reasons behind the actions, game theory focuses on players’ different actions influenced by the actions of other players. In the beginning of green retrofit, owners and tenants, as key decision makers, are interdependent and have different interests on the issue. For example, when the owners intend to administer green retrofit to improve their social reputation or to reduce maintenance cost, they have to consider the rental contracts with the tenants. On the contrary, when the tenants want to implement green retrofit to save energy cost, they have to consider the attitudes of the owners. Thus, the final green retrofit decision depends on the actions of both owners and tenants. In this case, game theory can be adopted to analyze the strategies of both parties. The results of the game theory analysis presented in this chapter can provide causal and solid proof for green retrofit decisions.

Game theory was established to identify the optimal solutions for economic behaviors (Von Neumann and Morgenstern, 1945). Nash (1950) developed a definition of an "optimum" strategy for multiplayer games. This strategy, which is well known as the "Nash equilibrium," indicates that every player cannot obtain a benefit by changing his own action; thus, the equilibrium is stable (Healy, 2006). Nash equilibrium is a type of game theory generally used to analyze the competition or collaboration problems between two decision makers, such as the prisoner's dilemma (Fudenberg and Tirole, 1991). Three basic elements exist in game theory, namely, player, strategy, and payoff. A player, who assumes absolutely rational self-interest, is an individual participant in the decision making on strategic choices. Strategy is a player's choice or action, which can either be a pure or mixed strategy in certain probabilities. Payoff is the interest a player accrues by adopting a strategy (Peng et al., 2014). Payoffs, which are quantitative, are normally described by a payoff matrix to illustrate the interest of a player on the basis of all decisions.

Game theory is widely used in research related to sustainable development and green building, particularly with regard to the relationship among stakeholders and their decision making. Gu et al. (2009) analyzed the strategies for energy-efficient housing developments with game theory by integrating four players, namely, administration, developers, architects, and inhabitants. The study identified several crucial issues in energy-efficient building development, and indicated that achieving the energy efficiency objective is difficult if the actions of all the players are based on their respective rational self-interest (Gu et al., 2009). However, this conclusion is relatively general and is not based on a concrete analysis of relationships and interests. Some studies have specified and quantified the interest of the players in games (Li et al., 2011; Mohsenian-Rad et al., 2010). Li et al. (2011) proposed a game theory model to analyze the energy-saving building market in China through a game of customers and developers, whose interests were calculated quantitatively. Game theory has also been used to evaluate and simulate energy consumption (Mohsenian-Rad et al., 2010; Soliman and Leon-Garcia, 2014). However, existing studies based on game theory are primarily for new energy efficiency building rather than for green retrofit.

This study mainly used game theory to model the decision-making behaviors of stakeholders, since the empirical data of decision-making behaviors is very limited and distorted. For example, most stakeholders prefer to show their positive attitudes rather than reluctance towards green retrofit to the public. This condition explains why the majority of cases in the existing studies are successful retrofit projects. Constrained by such realities, game theory is adopted to model decision-making behaviors using logical deduction rather than an empirical study.

4.4.3 Agent-based modeling

MASs have rapidly developed in the recent years because of the emergence of algorithms, approaches, technologies, and platforms. These systems include several intelligent agents that can represent real-world parties and follow different behavior criteria without global control, knowledge, and objectives (Ren and Anumba, 2004). An individual agent has incomplete resources, information, and capabilities to solve the whole problem. Hence, each agent attempts to maximize its utility by cooperating with other agents. A complex problem, which is in distributed spaces with different stakeholders and split interests, can be divided into relatively simple problems that can be assigned to intelligent agents. Similarly, MASs can handle problems concurrently to improve efficiency with agents working in parallel. Given their autonomy, cooperation, and learning characteristics (Nwana, 1996), intelligent agents can change consistently to adapt to an environment and interact with other agents. Therefore, MASs can realize real-time dynamic reactions with autonomous and flexible agents after changes in the environment. They can also attain system stability through convergence mechanism (Phanden et al., 2011). Given their characteristics and attributes, MASs are essentially suitable for solving various complex, distributed, and dynamic problems. For these reasons, MASs are ideal for use in the construction industry.

Numerous construction projects are complex systems with distributed heterogeneous stakeholders operating in a global dynamic environment. In the construction industry, fragmentation is a crucial problem (Ren and Anumba, 2004) for which collaboration has been identified as the CSF that can help solve the problem (Xue et al., 2012). However, geographically distributed teams, different backgrounds of participants, a dynamic environment, and conflicting interests negatively affect both collaboration and consensus. The MAS comprises different agents that can simulate the cooperation among different stakeholders in different places with varied interests. Modeling and simulating with this system can help address and analyze these issues. Therefore, the MAS is considered an appropriate approach to address the issue of fragmentation and improve collaboration in the construction industry, such as negotiation among stakeholders (Ren et al., 2003a; Xue et al., 2009), dynamic scheduling (Christodoulou, 2009; Kim and Paulson, 2003), collaborative design (Anumba et al., 2002; Chu et al., 2009; Ren et al., 2011), and field management (Kim and Kim, 2010).

Different from methods commonly used in previous studies (e.g., the statistical method and system dynamic modelling), MAS is a bottom-up method rather than top-down. It can model the behaviors of each stakeholder in green retrofit projects, focusing on their own objectives, benefits, costs and condition of environment. Based on negotiations and compromises among stakeholders, the system can reach an optimal decision. This bottom-up method can reveal the logic of stakeholders' motivations and strategies in decision making. The top-down methods analyze the decision making problem from a macro perspective without deep analysis of stakeholders. For example, the statistical method was applied to analyze the attitude of stakeholders to green retrofit through a questionnaire survey (Polzin et al., 2016). The results showed the attitude of stakeholders but did not explain the logic behind the results. Since all the decisions are made by stakeholders, it is very important to understand the details of stakeholder behaviors. Therefore, this study focused on stakeholders and applied MAS to investigate the decision making behaviors of stakeholders through this bottom-up method.

4.5 Summary of the Chapter

This chapter first discussed the research methodologies and illustrated the overall research framework. Detailed research methods were discussed separately. The document analysis was used to systematically investigate recorded information and published documents from a theoretical perspective, as well as collect sufficient statistical data from official documents issued by regional and national departments. The analytical tools used for data analysis included SNA, game theory and MAS, which together serve as a theoretical foundation for comprehensively understanding the decision making on green retrofit.

Chapter 5 Social Network Analysis of Key Stakeholders in Green Retrofit

5.1 Introduction

The aim of this chapter is to propose a two-mode network model to analyze the relationship between stakeholders and CSFs, as well as the influence of stakeholders on the success of projects. This chapter first introduces the influence of stakeholders on green retrofit. Then the process of the two-mode SNA is introduced stepwise. The results of SNA are highlighted at the end of the chapter.

5.2 Influence of Stakeholders on the Success of Green Retrofit

Stakeholder management largely accounts for the success of PM (Du and El-Gafy, 2012). In this chapter, stakeholders are defined as persons or a group of persons who are influenced by or are able to influence a project (Freeman, 1984). The strong cooperation of stakeholders is necessary for the success of projects, because a project can be considered a temporary organization of stakeholders to pursue an aim together (Jepsen and Eskerod, 2009). McElroy and Mills (2000) indicated that the purpose of stakeholder management is to achieve project success through the continuing development of their interrelationships. Therefore, how stakeholders influence the success of projects is an important and fundamental aspect of stakeholder management.

Most previous studies analyzed the priority of stakeholders by direct ranking, which hypothesizes a linear relationship between stakeholders and project success. However, construction projects are undertaken in a nonlinear, complex, and interactive environment, in which the influence of stakeholders cannot be easily identified by a linear model. This environment needs identification of underlying relationships between stakeholders and project success. Furthermore, traditional studies only answer the question “what,” that is, which stakeholders influence project success significantly, rather than how they influence the success and the relationships among them. To bridge these research gaps, CSFs are introduced as intermediate variables because the influence of stakeholders on project success can be interpreted through these factors. Figure 5.1 shows the proposed model of this study on the right side, where the problem is broken down into two parts: how stakeholders influence the CSFs, and how CSFs influence the success of projects. As the latter is relatively direct and has been revealed by previous studies (Xu et al., 2011; Yang et al., 2010), the current study focuses on analyzing the relationship between CSFs and stakeholders, as represented by the shaded area in Figure 5.1. This analysis is the main contribution of this study.

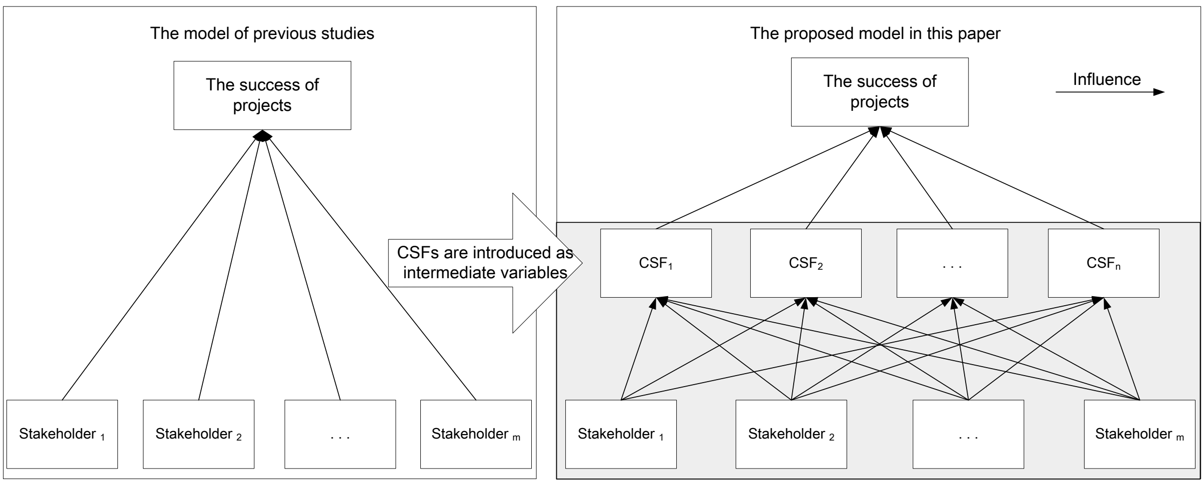


Figure 5.1. Theoretical hierarchy of stakeholders’ influence on the success of projects

The relationship between CSFs and stakeholders in Figure 5.1 can be analyzed through SNA, which is considered an effective method for understanding stakeholder management, especially in finding the underlying relationship structure (Bourne and Walker, 2006; Rowley, 1997). In contrast to traditional social sciences focusing on stakeholder attributes (e.g., stakeholder circle method), the SNA focuses on the relationships among stakeholders in a network (Yang, 2014), and this focus provides a nonlinear analysis of their influence on projects (Yang et al., 2011). Therefore, SNA is an appropriate method for representing the complex relationships between stakeholders and CSFs, and further revealing how stakeholders influence project success.

5.3 Process of the Two-Mode Social Network Model

The two-mode network, a type of SNA, is used to model the relationship between stakeholders and CSFs. It is different from the conventional one-mode network analysis, and helps to model and represent relationships between two sets through a bipartite graph. Various large, real-world networks may be modeled naturally by two-mode networks. Examples include actor–movie networks, where actors are linked to the movies they have acted in (Newman, 2001a); firm–city networks, where firms are linked to the cities they are located in (Neal, 2012); and author–paper networks, where authors are linked to their published papers (Newman, 2001b). However, analysis using the two-mode network has not been widely applied because there still exist few notions to analyze this network compared to the various notions to analyze classical one-mode networks (Latapy et al., 2008).

Yang (2014) summarized the process of conducting an SNA in five main steps: 1) identifying the boundary of the network, 2) assessing meaningful and actionable relationships, 3) visualizing the network, 4) analyzing the network data, and 5) presenting the results of the analysis. The process of the proposed two-mode network model, as derived from previous studies (Timur and Getz, 2008; Yang and Zou, 2014), is shown in Figure 5.2.

Process of Two-mode Network Model

	Identifying nodes	**Evaluating links**	**Visualizing and projecting**	**Analyzing network**	**Discussing results**
Aim	Identifying the boundary of network	Determining the Structure of network	Converting two-mode to one-mode network	Analyzing attributes of the network	Mining results and providing suggestions
Approaches	Focus groups; Interviews; Snowball sampling; Surveys; Workshops; Stakeholder circle methodology	Focus groups; Interviews; Surveys ; Workshops; Delphi method ;	Visualization software ; Top/bottom projection	Statistic analysis ; Graph theoretic approach	Comparative analysis; Inductive interpretation
Outcomes	A list of top and bottom nodes	A matrix of links among nodes	A projected one-mode network	Quantified analysis results of network	Result interpretations and suggestions

Figure 5.2 Process of the proposed two-mode network model

Step 1: Identifying the nodes of network

The aim of this step is to identify all the nodes, namely, the boundary of the network. For a two-mode network model, two lists of the top and bottom nodes need to be developed. Several approaches can be used to facilitate this step, mainly in two categories: literature review and experience-based methods.

Data captured from literature can define the scope of nodes according to related studies, surveys, and reports. Given that different studies may focus on different areas by different methods, the previous individual results may not be sufficient for the present study. A more comprehensive list of nodes can be obtained by combining the results of previous studies. The main advantage of this method is that it is an efficient way to identify possible existing factors. This method can also provide reliable references for identified factors and an analysis of the development trend. However, it can only summarize from previous results, rather than explore or find undefined and new factors. Hence, new factors from the current practice must be identified using the experience-based method.

The experience-based method is a suitable supplement to literature review. Focus groups, semi-structured interviews, workshops, and surveys are common approaches of this method. Usually, some experts involved in related subjects are invited to attend meetings to provide suggestions based on their experiences (Yang and Zou, 2014; Zou et al., 2014). The disadvantage is that it is difficult to compile a complete list of nodes from several workshops with a limited number of experts, or if limitations are present with respect to the experts' range of experiences. However, when seeking new factors in theory building, a grounded theory approach can be adopted (Glaser, 1992). Current good practices for the use of this approach recommend that conducting interviews for new factors should proceed until no new factors emerge from successive interviews (Glaser et al., 1968).

Step 2: Evaluating the links of network

A network comprises nodes and links, where the nodes are identified in Step 1 and the links are assessed in Step 2. Links in the network represent the relationships among nodes. These relationships can be defined in different ways, such as collaboration, information-sharing potential, rigidity, and supportiveness in a network (Yang, 2014). Prell et al. (2009) indicated that the relationships involving communication, decision making, and influence are the most frequently analyzed in practice. According to the different types of relationships, the value of links can be defined with different meanings, for example, the tightness of collaboration, degree of influence, and power in decision making. The link value is high when the nodes have strong interactions with each other, and vice versa. This step can be developed in parallel with Step 1 by using both the literature review and experience-based approaches. To minimize bias from dominant participants in the workshops, the Delphi method can be adopted to improve the results. Ideally, all the stakeholders identified in Step 1 should be involved in this step to achieve a consensus, but in reality, only some of the key stakeholders are engaged because of practical difficulties (Yang and Zou, 2014). A typical example of an evaluation matrix of a two-mode network model is shown in Table 4.3.

Step 3: Visualizing and projecting

On the basis of the nodes and links identified in Steps 1 and 2 respectively, the matrix can be visualized to a network figure. In this study, a two-mode network is proposed to represent the relationships between two sets of nodes; this is a different approach from the conventional one-mode network. The two-mode network can be visualized by various SNA software packages, including UCINET, NetMiner, NetDraw, and Pajek (Yang and Zou, 2014). It can then be converted to a one-mode network by projection. According to the specific issue, both top and bottom projections can be applied individually or synthetically.

Step 4: Analyzing the network

Based on the network after visualization and projection, quantitative analysis is adopted to mine information in the network structure, which is important for network analysis (Cross and Parker, 2004). Yang (2014) classified network analysis methods into network measures (e.g., density and cohesion) and individual measures (e.g., centrality and brokerage). The concept of centrality, as developed by Freeman (1979), is a prominent criterion for assessing the importance of nodes. Nodes need to be emphasized and assigned high priority in the network when they have high centrality values. Three types of centralities are widely used in network analysis, namely, degree, betweenness, and eigenvector centrality (Gould, 1967; Lienert et al., 2013; Neal, 2012; Yang and Zou, 2014). Degree centrality is defined as the link that a node shares directly with other nodes. It is commonly used for assessing the structural importance of nodes because it focuses on the local structure in which a particular node is embedded (Lienert et al., 2013). Betweenness centrality is the number of times a node is on the path between two non-interlinked nodes and is commonly used for accessing the power of nodes (Freeman, 1979). It refers to the argument that a node links with other nodes that are not directly linked previously (Lienert et al., 2013). Eigenvector centrality is a more sophisticated method proposed by Gould (1967). While the first two types hypothesize that all the nodes are equal, the eigenvector centrality considers the nodes to have different powers. The more powerful neighbors contribute more to the node centrality. All these centralities have their respective advantages and disadvantages (Prell et al., 2009), so they are used for comparison in this study.

In addition to the aforementioned network analysis methods, statistical methods are also important in quantitative analysis. Cluster analysis is used to categorize the nodes into several groups according to their similarities. Clusters in a classical one-mode network indicate the similarity and aggregation among nodes through their own attributes. In contrast, correlation coefficients and clusters in a two-mode network indicate the similarity and aggregation among nodes in one set through the relationship with nodes in another set. Therefore, the two-mode network model considers the two sets of nodes synthetically rather than independently. In this study, stakeholders and CSFs are analyzed together by a two-mode network model to provide the interrelationship between them. The node clusters can help understand the underlying relationship among nodes and improve categorization and management in projects.

Step 5: Discussing results and providing suggestions

The results of network analysis in the previous steps are discussed and summarized in this step. Suggestions are provided on the basis of the findings, which are mainly about stakeholder prioritization, relationship among stakeholders, stakeholders' influence on success, and policies to improve stakeholder management.

5.4 Results of Two-Mode Social Network Analysis

In this work, green retrofit in China is selected as the case study to illustrate the process of analyzing stakeholders' influence with the proposed two-mode network model. Green retrofit for buildings, which is considered an effective method to save energy and reduce GHG emissions (Sun and Liu, 2007; Xu and Chan, 2013), has attracted considerable attention in recent years. It can be defined as the incremental improvement of the building fabric and systems with the primary intention of improving energy efficiency and reducing carbon emissions. In China, 95% of the existing buildings have both high energy consumption and high carbon emissions, and the Chinese government has exerted tremendous efforts to promote green retrofit for such existing buildings (Xu and Chan, 2013). Numerous green retrofit projects have been implemented in recent years, and more are planned to be undertaken in the future.

The majority of previous studies focused on technical aspects of green retrofit, though some paid attention to stakeholder analysis and management. Examples of the latter include Miller and Buys (2008), who analyzed the interests, barriers, and objectives for energy-efficient retrofit from the tenants' perspective. Stiess and Dunkelberg (2013) discussed similar subjects from the homeowners' perspective. Menassa and Baer (2014) proposed a "House of Quality" model to quantify the requirements of stakeholders in green retrofit decisions. The key stakeholders in green retrofit process have also been analyzed and summarized by several scholars (Ali et al., 2008; Banaitiene et al., 2008; Juan et al., 2009; Kaklauskas et al., 2004).

Although previous studies have discussed various aspects of stakeholder management in green retrofit, few have focused on the relationship between stakeholders and CSFs, and how the former influences the success of projects. To bridge this research gap, this study applied the two-mode network model to build the relationship between stakeholders and CSFs, and then analyzed the stakeholders' prioritization and their influence on project success. The aforementioned processes are followed in a stepwise manner as follows.

5.4.1 The network

This study uses both literature review and experience-based methods to identify the stakeholders and CSFs of green retrofit. First, the lists of stakeholders and CSFs were identified from existing literature, and then a series of in-depth interviews were conducted to confirm, refine, and categorize these lists. Five semi-structured interviews were conducted with 16 experts, all with experience in green retrofit projects. To enhance the reliability of the results, these interviews were conducted from the north to south of China, including Beijing, Shenzhen, Guangzhou, and Hong Kong. The interviews lasted from 30 minutes to 2 hours throughout March to July 2014. The details of the interviews are shown in Table 5.1.

The interviews investigated the issues about CSFs in green retrofit projects, stakeholders related to project success, and categorization of CSFs and stakeholders. The lists of CSFs and stakeholders were developed by integrating the information from interviews and literature, which are listed in Tables 5.2 and 5.3. Note that this study only focuses on green retrofit related CSFs and stakeholders.

Table 5.1 Details of the semi-structured interviews

Interview No.	Location	Number of interviewees	Roles in projects	Company types
1	Hong Kong	10	Project manager, technical specialists, purchasing managers	Client
2	Beijing, Mainland China	1	Designer	Design institute
3	Beijing, Mainland China	1	Administrative manager	Design institute
4	Shenzhen, Mainland China	2	Contractor manager, supervisor	Third-party institute (authorized by the government to audit projects)
5	Guangzhou, Mainland China	2	Facility managers	Facility management

Table 5.2 Main stakeholders of green retrofit projects

Code	**Stakeholder**	Kaklauskas et al. (2004)	Juan et al. (2009)	Miller and Buys (2008)	Kaklauskas et al. (2008)	Banaitiene et al. (2008)	Gultekin et al. (2013)	Ali et al. (2008)	Xu et al. (2011)	Cronin Jr et al. (2011)	Rosenfeld and Shohet (1999)
S1	Owner/client	√		√	√	√	√				
S2	Tenant/user	√		√	√						
S3	Property manager	√		√	√						
S4	Designer	√			√	√	√				
S5	Contractor	√		√		√	√				
S6	Supplier	√				√					
S7	Sub-contractor							√			
S8	Government	√			√						
S9	Financial institution/bank		√	√	√						
S10	Energy service company			√					√		
S11	Industry association	√									
S12	NGO/community					√				√	
S13	Research institution							√			√

Table 5.3 CSFs of green retrofit projects

Category	Code	CSF	Literature
Economics	C1	Cost	(Chidiac et al., 2011; Gultekin et al., 2013; Kaklauskas et al., 2004)
	C2	Who invests	(Fuerst and McAllister, 2011; Menassa and Baer, 2014)
	C3	Profit distribution among stakeholders	(Davies and Osmani, 2011)
	C4	Interruptions in operations	(Kasivisvanathan et al., 2012; Miller and Buys, 2008)
	C5	Interest rate	(Kaklauskas et al., 2004)
	C6	Occupancy type	(Ma et al., 2012; Rhoads, 2010)
	C7	Who gets energy-saving benefits	(Fuerst and McAllister, 2011)
	C8	Subsidies/tax reduction	(Davies and Osmani, 2011; Kaklauskas et al., 2004; Ma et al., 2012)
	C9	Rent increases after retrofit	(Fuerst and McAllister, 2011; Thomas, 2010)
Building information and environment	C10	Existing building environment	(Ma et al., 2012; Mickaityte et al., 2008)
	C11	Existing building condition	(Ali et al., 2008; Menassa and Baer, 2014; Mickaityte et al., 2008; Xu et al., 2011)
	C12	Existing facilities condition	(Andrews et al., 2011; Menassa and Baer, 2014; Mickaityte et al., 2008)
	C13	Existing building information modeling	(Andrews et al., 2011; Volk et al., 2014)
	C14	Existing building evaluation	(Mickaityte et al., 2008)
Sociocultural	C15	Clear vision	(Trust, 2008)
	C16	Cooperation among stakeholders	(Gultekin et al., 2013; Trust, 2008)
	C17	Information sharing	(Ma et al., 2012; Mickaityte et al., 2008)
	C18	Users' behavior and demand analysis	(Caccavelli and Gugerli, 2002; Ma et al., 2012)
	C19	Project organization and management	(Gultekin et al., 2013)
	C20	Experience sharing and education	(Davies and Osmani, 2011; Kasivisvanathan et al., 2012; Rhoads, 2010)
	C21	Cultural traditions	(Mickaityte et al., 2008)
Technology	C22	Maturity of technology	(Ma et al., 2012; Mickaityte et al., 2008)
	C23	Complexity of technology	(Davies and Osmani, 2011)
	C24	Maintainability	(Caccavelli and Gugerli, 2002)
	C25	Information technologies and computerization level	(Mickaityte et al., 2008)
	C26	Collaborative design and automation	(Ali et al., 2008; Korkmaz et al., 2010; Lapinski et al., 2006)
Policy and standard	C27	Clear government program and policies	(Davies and Osmani, 2011; Ma et al., 2012; Mickaityte et al., 2008)
	C28	Clear criteria and standards	(Mickaityte et al., 2008; Miller and Buys, 2008; Rhoads, 2010; Xu et al., 2011)

The relationship between the stakeholders and CSFs identified in Step 1 was evaluated through a 13×28 matrix with 364 interactions for assessing (see Appendix I)[1]. The workshop was conducted in Beijing in July, 2014. According to practical difficulties, the workshop cannot involve all stakeholders. Therefore, five key professionals were invited to the workshop: two designers, one client, one contractor, and one supplier. The interview lasted for three and half hours. First, the Delphi method was used to collect independent evaluations from the professionals; this took about one hour. Next, an open discussion was conducted to reach a consensus of their evaluation. The evaluation used a five-point Likert scale, where 4 is Extremely strong influence, 3 is Strong influence, 2 is medium influence, 1 is Very small influence, and 0 is No influence. Through this workshop, an evaluation matrix of relationships between 28 CSFs and 13 stakeholders was developed, shown in Figure 5.4.

The two-mode network of stakeholders and CSFs was established based on the nodes identified in Step 1 and the links evaluated in Step 2. In this stakeholder–CSF scenario, ▽ in the two-mode network refers to the group of stakeholders, △ refers to the group of CSFs, and E refers to the tightness of relationship between stakeholders and CSFs. The stakeholder–CSF network is visualized from Table 5.4, shown in Figure 5.3. The nodes in blue are stakeholders and the other nodes are CSFs, where the different shapes indicate different CSF categories. The links between stakeholders and CSFs show the relationship between them. The codes C1-C28 and S1-S13 represent CSFs and Stakeholders respectively.

[1] Public buildings include commercial buildings, schools, museums and etc. In China, most green retrofit projects of public buildings are for commercial buildings according to public information of the China government. Since the data of green retrofit projects for commercial buildings was more sufficient than other public buildings, this case study focused on commercial buildings.

Table 5.4 CSF-stakeholder matrix based on data from the workshop

CSFs	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13
C1	4	2	2	3	2	2	2	2	2	3	0	0	1
C2	4	1	2	2	2	2	2	3	2	4	0	0	1
C3	4	2	3	1	1	1	1	2	1	2	0	0	0
C4	3	4	4	2	2	1	2	2	1	1	0	0	1
C5	3	0	1	1	0	1	1	2	3	2	0	0	0
C6	3	3	3	2	2	1	1	1	0	1	0	0	0
C7	4	3	3	1	1	1	1	2	1	2	0	0	0
C8	4	2	2	1	1	1	1	4	2	2	1	1	1
C9	4	4	3	1	0	0	0	1	2	1	0	0	0
C10	3	3	3	2	1	1	0	1	0	1	0	0	0
C11	3	3	2	3	1	1	1	1	0	1	0	0	1
C12	3	3	3	3	1	2	2	1	0	2	0	0	0
C13	3	2	3	3	2	2	2	1	0	0	0	0	1
C14	3	2	3	2	1	2	1	2	1	2	1	1	2
C15	3	2	2	3	1	1	1	3	1	1	1	1	2
C16	3	1	2	2	2	2	2	3	2	3	0	0	0
C17	3	2	3	3	1	1	2	3	1	3	0	0	0
C18	3	3	3	3	1	1	1	3	0	2	1	0	0
C19	3	2	2	2	3	2	3	2	1	2	0	0	1
C20	3	1	2	4	2	1	1	3	0	2	1	0	2
C21	3	2	3	3	0	1	0	3	0	2	1	1	2
C22	4	1	3	4	2	2	1	3	1	3	1	0	1
C23	4	1	3	4	3	2	2	3	1	2	0	0	1
C24	4	2	4	3	2	2	2	3	1	2	0	0	1
C25	3	2	3	3	2	1	1	2	0	3	0	0	1
C26	4	2	3	3	2	1	1	2	0	2	0	0	1
C27	4	2	2	3	2	2	2	4	2	3	1	1	1
C28	3	1	2	4	3	3	3	4	1	3	1	1	2

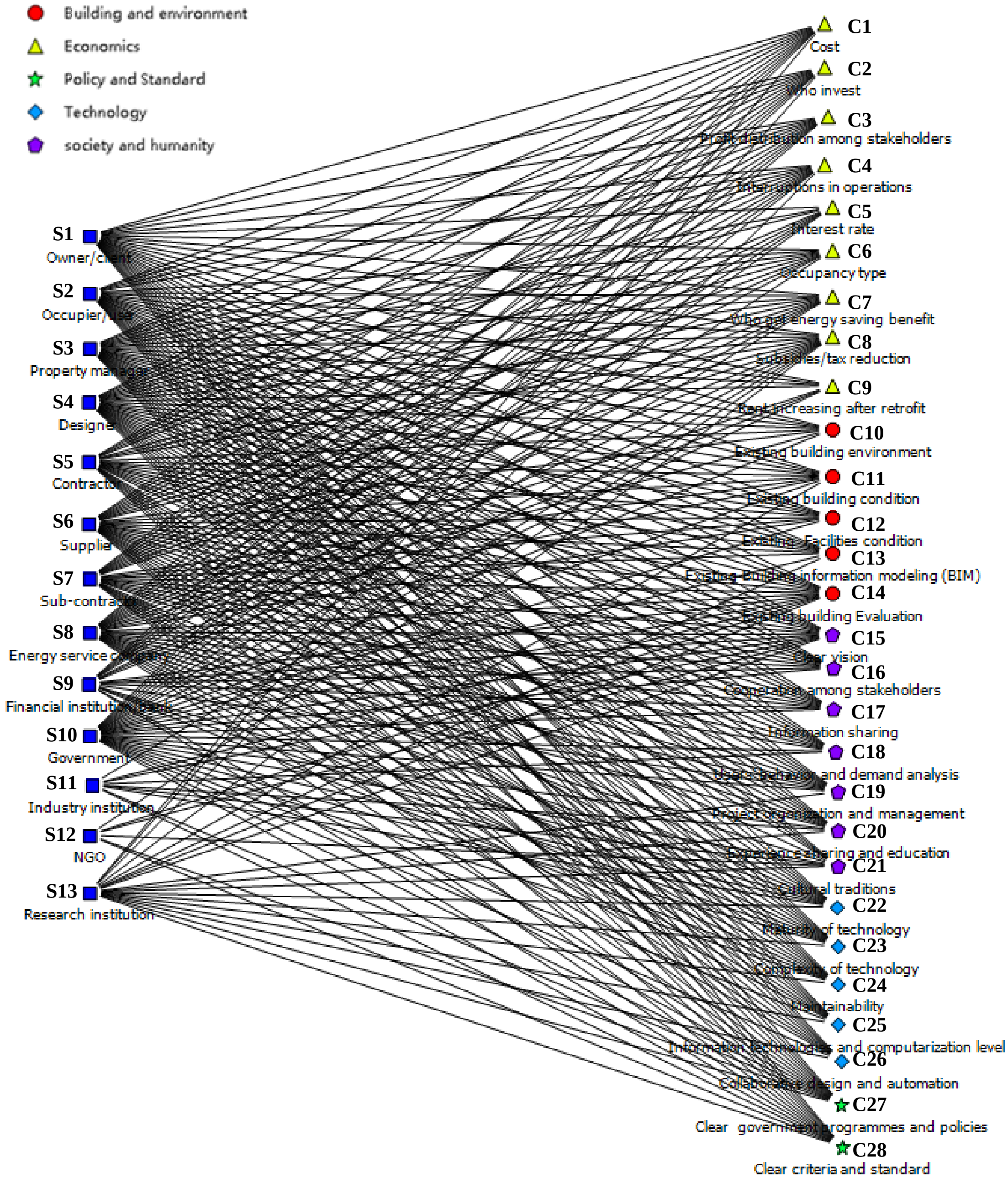


Figure 5.3 Two-mode network of stakeholders and CSFs in green retrofit

This study uses top projection to convert the two-mode network to a one-mode network, that is, the network of stakeholders, as shown in Table 5.5 and Figure 5.4. In the top projected network, the nodes comprise 13 stakeholders and the links show the relationships among them. A novel way of color-coding is used, different from the previous network analysis of stakeholders, such that the links in the projected network indicate the tightness of the relationship related to the CSFs. The color ranges from red to violet to indicate the degree of relationship. The colors of links nearer red are higher in degree, which means the linked stakeholders have a tighter relationship and stronger influence on each other with respect to project success. Conversely, the colors nearer blue/violet are low in degree, which means the linked stakeholders have a comparatively looser relationship and weaker influence on each other.

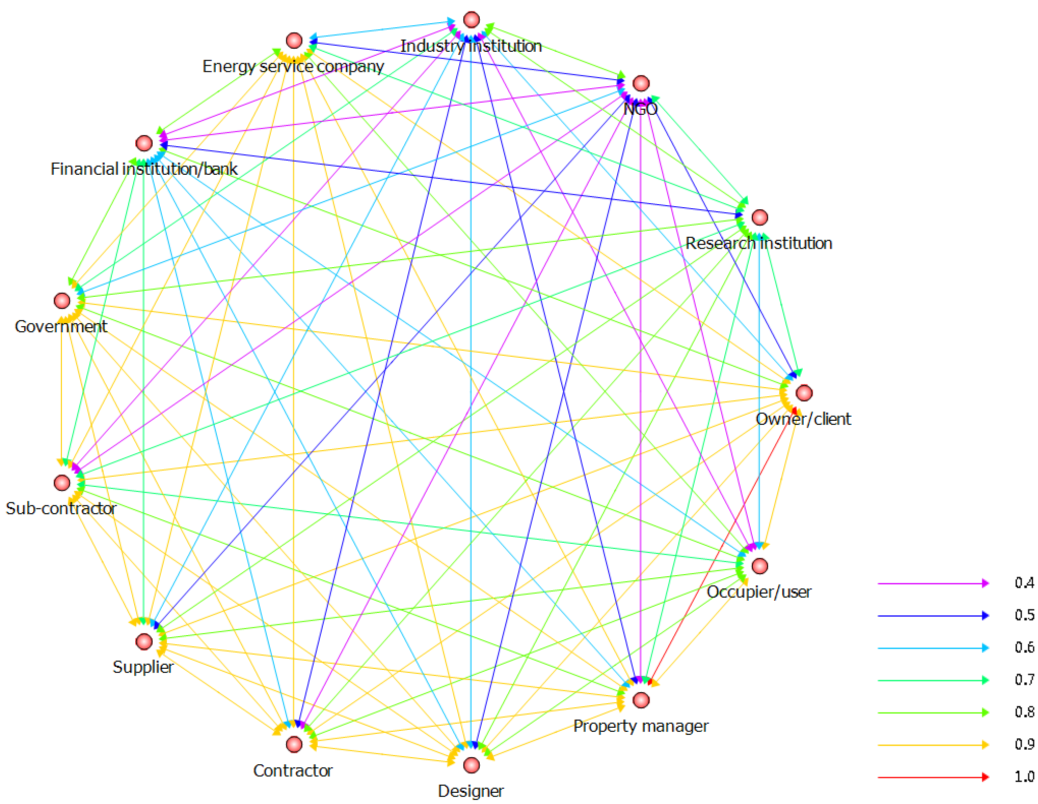


Figure 5.4 Projection of the relationships among stakeholders related to CSFs

Table 5.5 Specific degree of the projected relationship among stakeholders related to CSFs

Stakeholders	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13
S1	1	0.9	1	0.9	0.9	0.9	0.9	0.9	0.8	0.9	0.6	0.5	0.7
S2		1	0.9	0.8	0.8	0.8	0.7	0.8	0.6	0.8	0.4	0.4	0.6
S3			1	0.9	0.9	0.9	0.8	0.9	0.6	0.9	0.5	0.4	0.7
S4				1	0.9	0.9	0.9	0.9	0.6	0.9	0.6	0.5	0.8
S5					1	0.9	0.9	0.9	0.6	0.9	0.5	0.4	0.8
S6						1	0.9	0.9	0.7	0.9	0.6	0.5	0.8
S7							1	0.9	0.7	0.9	0.4	0.4	0.7
S8								1	0.8	0.9	0.7	0.6	0.8
S9									1	0.8	0.4	0.4	0.5
S10										1	0.6	0.5	0.7
S11											1	0.8	0.8
S12												1	0.7
S13													1

5.4.2 Key stakeholders

Stakeholder prioritization can be represented by centrality, as discussed in Section 5.3. The three types of centralities, as defined in Section 5.3, are applied to analyze the importance of CSFs. The priority rankings of stakeholders in accordance with these three types of centralities are shown in Table 5.6 and Figure 5.5.

Table 5.6 Stakeholder prioritization based on different types of centralities

Stakeholders	Degree centrality		Betweenness centrality		Eigenvector centrality	
	Value	**Rank**	**Value**	**Rank**	**Value**	**Rank**
Owner/client	0.09551098	1	0.11627907	1	0.178402	1
Property manager	0.09551098	2	0.11627907	2	0.138636	2
Designer	0.09551098	3	0.11627907	3	0.136447	3
Government	0.09551098	4	0.11627907	4	0.127691	4
Energy service company	0.09169054	5	0.107334526	5	0.110179	5
Tenant/user	0.09169054	6	0.103756708	6	0.106166	6
Supplier	0.09169054	7	0.105545617	7	0.077709	8
Contractor	0.08500478	8	0.084078712	8	0.084276	7
Sub-contractor	0.08500478	9	0.084078712	9	0.07625	9
Financial institution/bank	0.06112703	10	0.04293381	10	0.048887	10
Research institution	0.06112703	11	0.041144902	11	0.044874	11
Industry association	0.03056351	12	0.007155635	12	0.017877	12
NGO/community	0.02005731	13	0.001788909	13	0.011675	13

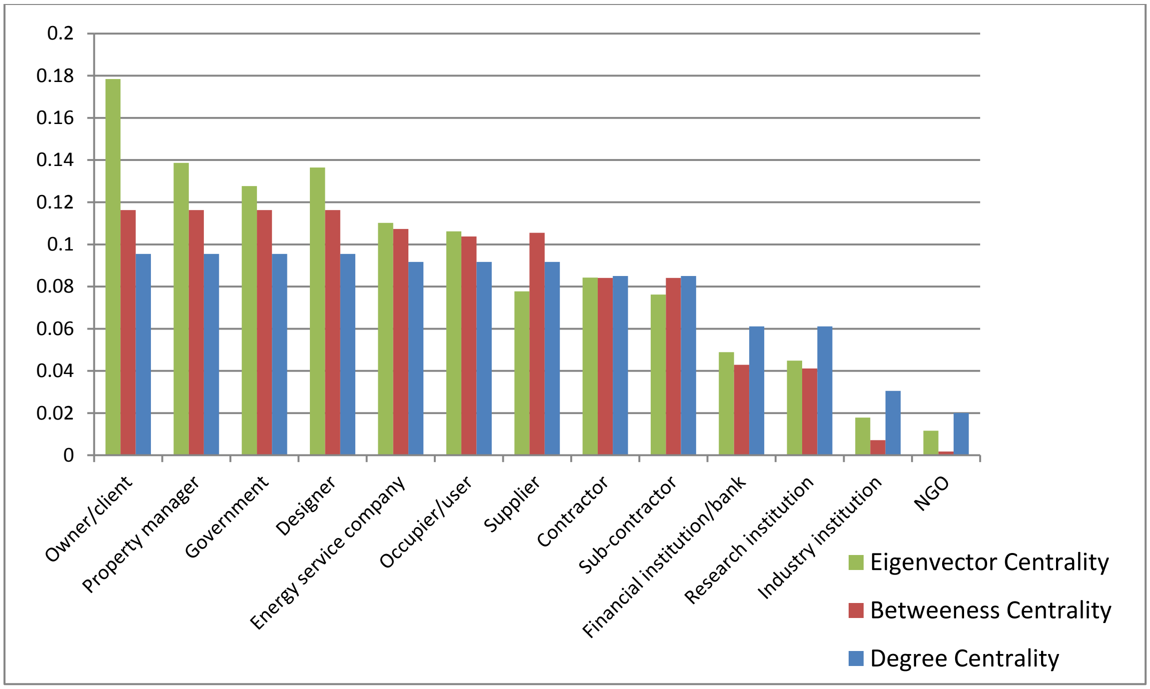


Figure 5.5 Comparison of prioritization based on different types of centralities

Cluster analysis is adopted to categorize stakeholders according to their similarity. The tree diagram developed by Ward's method (Mojena, 1977) is shown in Figure 5.6. The horizontal axis represents the distance of similarity, which indicates the similarity of stakeholders. The smaller the value of distance is, the more similar the stakeholders are. The vertical axis represents the stakeholders, who are rearranged by clusters. Five clusters are highlighted in Figure 5.6, namely, cluster 1 (owner/client, property manager, tenant/user), cluster 2 (supplier, contractor, sub-contractor), cluster 3 (government, energy service company, designer, research institution), cluster 4 (financial institution/bank), and cluster 5 (industry association, NGO/community).

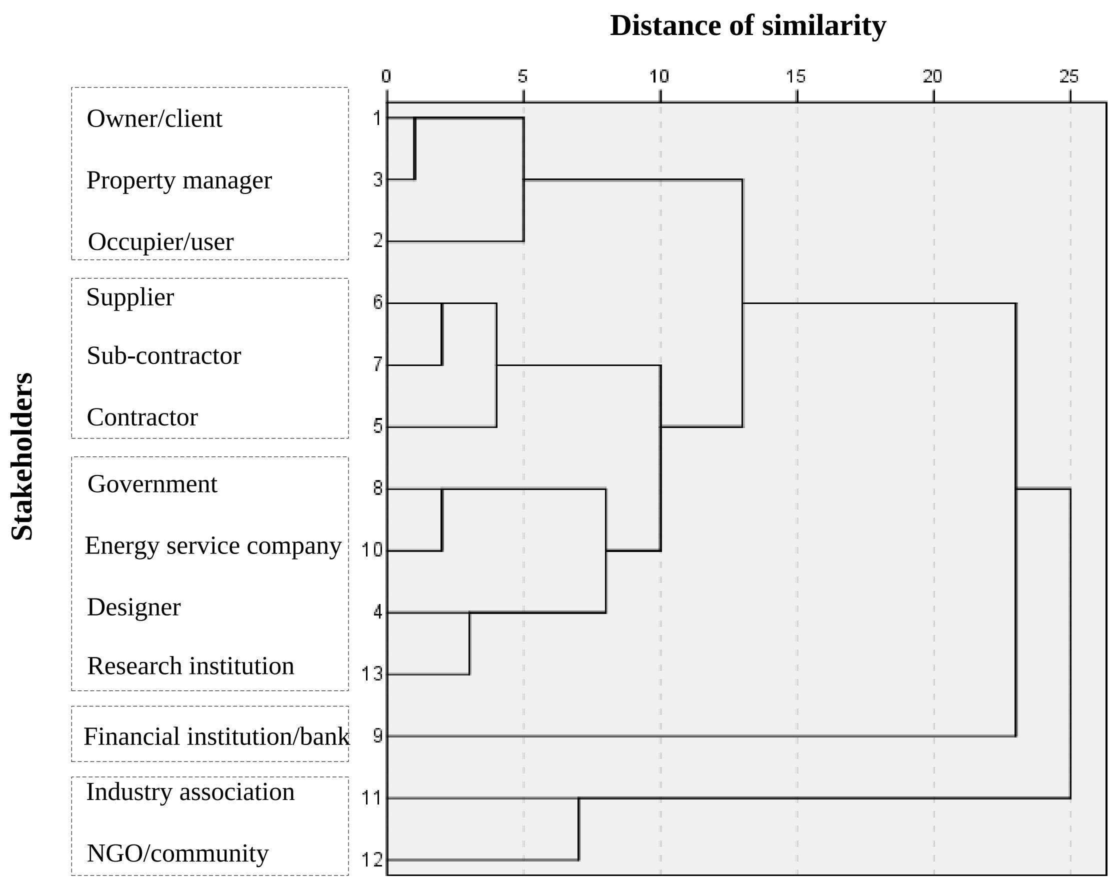


Figure 5.6 Tree diagram of cluster analysis for stakeholders

5.4.3 Discussion

The structure of the two-mode network shown in Figure 5.3 illustrates the interrelation between stakeholders and CSFs. The linked stakeholders and CSFs are related to each other, and the value of the link represents the power of influence. For example, the property manager is related to all the CSFs and has the strongest influence on "interruptions in operations" because the score of the link between them is the highest. On the contrary, NGO/community only links to six CSFs with a low value of "1," which implies a very small influence on these six CSFs and no influence on the other CSFs. Therefore, in stakeholder analysis and management, the structure of this two-mode network can help project managers understand the stakeholders' power of influence on every CSF. Furthermore, stakeholders can be compared to show the differences of their power on different CSFs. From the CSF perspective, if an issue of a specific CSF arises, the most powerful stakeholder that influences this CSF can be selected and focused on, thus facilitating efficient project management.

Relationships among stakeholders, shown in Figure 5.4, indicate the closeness of their relationship with the success of projects. The value of links is normalized in [1, 0], where "1" represents the closest relationship and "0" represents no relationship. The higher the link value, the closer the two stakeholders' relationship with CSFs. For example, the link value between the owner/client and the property manager is "1," which implies their similar influence on the success of projects. However, owner/client (S1) has a significantly different influence on project success than NGO (S12), given that the value of the link between them is only 0.5. Stakeholders in close relationships have similar issues, interests, barriers, risks, and influences on project success. Therefore, this indicator can improve requirements analysis, risk assessment, and troubleshooting in project management.

The results of prioritization by degree and betweenness centrality methods are both the same and slightly different from the result by eigenvector centrality method in numbers seven and eight. Such results indicate that the prioritization is unified and reliable because it is verified by different methods. Owner/client, property manager, designer, and government are the first four important stakeholders; they obtained the same score in the degree and betweenness centrality methods. Research institutions, industry associations, and NGO/community are the last three stakeholders; they were not participants in the green retrofit projects or had direct economic relationships. Specifically, the values of the last two stakeholders are significantly below that of the others, indicating that they are in only a peripheral position within the stakeholder circle (Yang, 2014).

Stakeholder categorization is implemented by clustering methods. The five clusters, as shown in Figure 5.6, are as follows.

Cluster 1 involves owner/client, property manager, and tenant/user, who are end-use stakeholders. They have a direct interaction with the retrofitted building. An owner/client owns the building and benefits from it. Tenants/users living in the building are directly affected by the environment of the building. The property manager manages the operation of the building. These stakeholders are the most familiar with the building condition, and will be affected most strongly by retrofitting. Therefore, they are the core stakeholders in decision making, especially in deciding whether to retrofit at the beginning stage.

Cluster 2 involves contractor, sub-contractor, and supplier, who are construction stakeholders. They have direct relationships with the green retrofit projects but not with the retrofitted buildings. They play major roles in the construction phase and need close cooperation.

Cluster 3 involves government, energy service companies, designer, and research institutions, who are consulting and service stakeholders. They are not participants in construction, but provide technical support and solve some special issues.

Cluster 4 involves financial institutions/banks, who are finance stakeholders. Financial institutions mainly offer financial support for green retrofit projects.

Cluster 5 involves industry associations and the NGO/community, who are supervision stakeholders. Although they do not have a direct relationship with green retrofit projects, they can supervise whether or not the projects follow industrial standards, environmental criteria, policies, and laws.

A comparison of the prioritization and cluster results reveals that the tenants are underestimated in stakeholder analysis. Tenants are clustered in the same group with clients as one of the core stakeholders and as the direct users of the buildings. However, they are only number six in the priority rank. A main difference between green retrofit and new green building projects is that the former tenants are occupants in the existing buildings. Green retrofit may influence the occupants in their operation, health, income, and rent, whereas occupants can strongly influence the CSFs and the success of a project during its life cycle. Juan et al. (2009) indicated that the influence of tenants increases the difficulty and risk of the retrofit process compared to projects for new buildings, because the cooperation and participation of tenants are required in the existing building retrofits (Miller and Buys, 2008). Therefore, additional focus should be directed toward occupants in green retrofit projects.

The aim of this two-mode social network analysis is to identify the key stakeholders in green retrofit. The identified key stakeholders will be involved in the game theory-based model, which is the next step of this study, illustrated in Chapter 6. Since this study investigates decision making on green retrofit from stakeholder perspective, the analysis of game theory-based model and agent-based platform focuses on stakeholders. The CSFs in the stakeholder analysis are used as intermediate variables to identify key stakeholders in green retrofit. Therefore, after identifying key stakeholders in green retrofit, the CSFs are not used in the following steps of this study.

5.5 Summary of the Chapter

This chapter originally developed a two-mode network model to analyze stakeholders' influence on project success. CSFs were introduced as intermediate variables between stakeholders and project success. The relationship of stakeholders and CSFs could be modeled by the two-mode network, through which the former's influence on the latter was revealed, and the influence on success could be better understood in advance.

A case study on green retrofit in China was conducted to illustrate how the proposed two-mode network model operates. The results of this two-mode network analysis can help understand stakeholder characteristics and how they influence the success of projects.

Chapter 6 Decision Making of Key Stakeholders in Green Retrofit

6.1 Introduction

This chapter aims to reveal the underlying logic of decisions on green retrofit and optimize the decisions of key stakeholders, which are owners, tenants and government identified in Chapter 5. The decision-making behaviors of the key stakeholders are modelled under the current market constraints based on game theory. This chapter first uses the complete information game model to analyze the relationship between owners and tenants without incentives from government. The results show that both owners and tenants are reluctant to green retrofit. Then, an incomplete information game model is built to analyze the decision-making behaviors of owners, tenants, and government. The results show the optimized decision making of key stakeholders and provide several policy suggestions to promote green retrofit.

6.2 Game Model between Owners and Occupiers without Incentives

6.2.1 Problem definition

The problem of developing a strategy on green retrofit is defined as a non-cooperative game between the owners and occupiers of existing buildings. The critical elements for the game analysis are specified below.

1) Players: Two players are involved in the game, namely, the owner and the occupier, as elaborated in Section 2.2.

2) Strategies: In general, the owner is the entity who establishes the initiative to retrofit and provides the initial retrofit plans. However, occupiers have become increasingly active in green retrofit projects in recent years. Given that numerous buildings have been retrofitted successfully over the past few years, such experiences have attracted the occupiers because of the learning effect. In 2015, 81 occupiers actively raised 16 million CNY to finish the green retrofit project in the International Trade Center of Shenzhen, China (Xiao, 2015). Therefore, both the owner and occupier in this game have two strategies, namely, "initiative to retrofit" and "reluctant to retrofit." The former strategy refers to the initiative to conduct green retrofit, whereas the latter is the resistance to the implementation of green retrofit but retains regular operations.

3) Payoffs: The payoffs of owners and occupiers depend on their respective strategies, which are shown in the payoff matrix in Figure 6.1. B_{ow11}, B_{ow12}, B_{ow21}, and B_{ow22} represent the benefits of an owner under different strategies, whereas B_{oc11}, B_{oc12}, B_{oc21}, and B_{oc22} represent the benefits of an occupier.

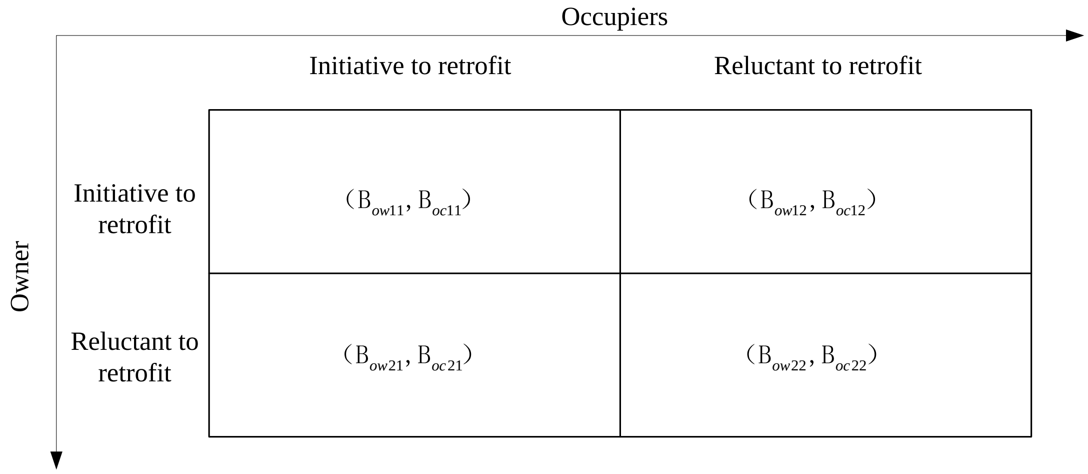


Figure 6.1 Payoff matrix of retrofit strategy for owner and occupier

4) Drivers and barriers for owners and occupiers

The drivers and barriers of retrofit for owners and occupiers are coded based on the literature review in Sections 2.2.2 and 2.2.3, as shown in Table 6.1.

Table 6.1 Drivers and barriers of green retrofit for owners and tenants

Stakeholders	Drivers	Barriers
Owners	D_{OW}1: Higher rent D_{OW}2: Lower maintenance cost D_{OW}3: Subsidies/tax reduction D_{OW}4: Return on investment D_{OW}5: Higher occupancy rate D_{OW}6: Risk reduction (avoid premature obsolescence, energy cost increasing) D_{OW}7: Longevity D_{OW}8: Rise in asset value D_{OW}9: Reputation enhancement D_{OW}10: Social responsibility D_{OW}11: Tenants' satisfaction	B_{OW}1: High retrofit cost B_{OW} 2: Long payback periods B_{OW} 3: Finite capital B_{OW} 4: Interruptions in operations B_{OW} 5: Risk of retrofits B_{OW} 6: Highly complex design analysis and solution B_{OW} 7: Lack of building information B_{OW} 8: Lack of retrofit experience
Tenants	D_{OC}1: Lower total cost (including potentially higher rent and lower energy cost) D_{OC}2: Productivity improvement D_{OC}3: Comfort enhancement D_{OC}4: Social responsibility	B_{OC}1: Higher rent B_{OC}2: Interruptions in operations B_{OC}3: Risk of retrofits (energy may not be saved by retrofit) B_{OC}4: Lack of understanding or interest about the environment B_{OC}5: Lack of information B_{OC}6: Possibility of relocation (tenants may not bear interruptions or higher rent)

6.2.2 Retrofit decision for owner-occupied building

The owner-occupied building is discussed first because it is the simplest occupancy type and can be used as a baseline. In this type of building, the tenants also own the building and they can make retrofit decisions by themselves without negotiation. The income of the owners comes from the energy cost saving, maintenance cost saving, building value increase, and public impact. The costs are retrofit investment and operation disturbance. Rent, occupancy rate, and turnover rate are not considered in this owner-occupied situation. These variables are described in Table 6.2. The column of "Driver/Barrier" shows the corresponding relation between the variables and the drivers or barriers illustrated in Tables 2.1 and 2.2. This study assumes that the decision to retrofit depends on the benefits that the decision makers can reap from retrofit. Therefore, non-economic factors, such as lack of building information ($B_{OW}6$) and lack of retrofit experience ($B_{OW}7$), are not considered in this analysis. Subsidies and tax reduction ($D_{OW}3$) are not included in the variables because the model is focused on the retrofit decisions without market interventions. In fact, the Chinese government only provides incentive funds for the energy-efficiency retrofit of residential buildings in the northern heating area of China (Zhou et al., 2010) and of public buildings in a few pilot cities. Most areas are not funded by the government, a condition that is consistent with this model. The risks of retrofits ($D_{OW}5$/$B_{OW}6$) are also not considered in this analysis but are discussed in Section 6.2.5.

Table 6.2 Decision variables in owner-occupied buildings

Stakeholder	Variable	Definition	Driver/Barrier
Owner	B_{ow}	benefit of a building owner	$D_{OW}1/4$
	S_e	energy saving through green retrofit	$D_{OW}4$
	S_o	operation saving through green retrofit	$D_{OW}2$
	ΔV	building value increase through green retrofit	$D_{OW}7/8$
	ΔP	public impact through retrofit	$D_{OW}9/10/11$
	I	investment of building retrofit	$B_{OW}1/2/3$
	D	disturbance of business during retrofit	$B_{OW}4$

B_{ow}^{oo} can then be calculated with the following formula, where the superscript "*oo*" represents the owner-occupied condition:

$$\mathrm{B}_{ow}^{oo}=S_e{}^{oo}+S_o{}^{oo}+\Delta V^{oo}+\Delta P^{oo}-I^{oo}-D^{oo} \quad (1)$$

All variables represent the life cycle value, which is an efficient method for conducting an economic analysis of the building retrofit issues (Ouyang et al., 2011). Various factors may influence the decision making on retrofit in different levels. The factors related to the direct economic profit, such as I^{oo}, D^{oo}, and $S_e{}^{oo}$, may be considered as high priority; otherwise, they are regarded as relatively low priority (e.g., ΔP^{oo}). The difference among these factors depends on specific projects and on the evaluation of the owners. When $B_{ow}^{oo} > 0$ in this owner-occupied scenario, the owners can benefit from the green retrofit and will choose it as a strategy; otherwise, the green retrofit will not be implemented. The building owners and occupiers in this scenario have no game because the decision is made only by the owners.

6.2.3 Retrofit decision for single-occupied building

In the scenario of a single-occupied building, two players, namely, the owner and the single occupier, are in the game for green retrofit decision making. The advantages and disadvantages of green retrofit for the owner are the economic aspects and social influences of the process. The economic aspects include operation cost saving from green retrofit, building value increasing, and investment. The social influences pertain to the reputation of a company, enterprise social responsibility, environmental impact, and other factors related to the society. To confirm the preliminary proposal and decide on the implementation, the owner and the occupier must communicate and negotiate with each other, which may cost time, money, and human resource. In addition to the factors illustrated in Section 6.2.2, the increasing rent and coordination costs are the influencing factors for owners in this scenario.

For single occupiers, the advantages and disadvantages of green retrofit pertain primarily to the economic aspects and social influences. The economic aspects include energy cost saving from green retrofit, rent increase, and disturbance of business during retrofitting. The social influences are the same as the social factors for the owners. Different from the scenario of an owner-occupied building, the rent and disturbance of the business during retrofitting are accrued to the occupiers rather than to the owners. These variables are described in Table 6.3. The non-economic factors, such as comfort enhancement ($D_{OC}3$), lack of understanding or interest about the environment ($B_{OC}4$), and lack of information ($B_{OC}5$), are not considered.

Table 6.3 Decision variables in single-occupied buildings

Stakeholder	**Variable**	**Definition**	**Driver/Barrier**
Owner	ΔR	increased rent by retrofit	$D_{OW}1/5$
	C_c	coordination cost for retrofit	$B_{OW}1$
Occupier	B_{oc}	benefit of building occupier	$D_{OC}1/2$
	S_e	energy saving through green retrofit	$D_{OC}1$
	ΔR	increased rent through retrofit	$B_{OC}1$
	D	disturbance of business during retrofit	$B_{OC}2$
	ΔP	public impact through retrofit	$D_{OC}4$

The payoff matrix for the owners and occupiers in a single-occupied building is shown in Figure 6.2, where the superscript "*so*" represents the single-occupied condition.

Owner \ Occupier	Initiative to retrofit	Reluctant to retrofit
Initiative to retrofit	$B^{so}_{ow11}=S^{so}_{o11}+\Delta V^{so}_{11}+\Delta R^{so}_{ow11}+\Delta P^{so}_{11}-I^{so}_{11}-C^{so}_{11}$ $B^{so}_{oc11}=S^{so}_{e11}+\Delta P^{so}_{11}-D^{so}_{11}-\Delta R^{so}_{oc11}$	$B^{so}_{ow12}=S^{so}_{o12}+\Delta V^{so}_{12}+\Delta P^{so}_{12}-I^{so}_{12}-C^{so}_{c12}$ $B^{so}_{oc12}=S^{so}_{e12}+\Delta P^{so}_{12}-D^{so}_{12}$
Reluctant to retrofit	$B^{so}_{ow21}=S^{so}_{o21}+\Delta V^{so}_{21}+\Delta P^{so}_{21}$ $B^{so}_{oc21}=S^{so}_{e21}+\Delta P^{so}_{21}-D^{so}_{21}-I^{so}_{21}$	$B^{so}_{ow22}=0$ $B^{so}_{oc22}=0$

Figure 6.2 Payoff matrix for owner and occupier in single-occupied buildings

On the basis of this adapted matrix, the following scenarios are investigated to identify the Nash equilibrium under the single-occupied condition.

The action of the occupier when the owner has the initiative to retrofit

Green retrofit can be implemented smoothly when the owner has the initiative to implement the approach and the occupier is also interested in it. The occupier should be willing to pay additional rent to the owner to compensate for the additional costs of implementing green retrofit (Fuerst and McAllister, 2011). This scenario occurs mostly in government and large private organizations, where sustainable development is considered an essential factor in building selection (Miller and Buys, 2008). The occupier tends to pay additional rent ΔR^{so}_{oc11}. In cases where the owner decides to implement green retrofit but the occupier is reluctant, green retrofit can still be implemented because the owner is the main decision-maker. The reluctant occupier, as a large organization, cannot move out because of the long rental contract and high relocation cost, but could take the position of non-cooperation. Given the strong influence of the owner's income and profit, the single occupier will have relatively high negotiation capacity and will not pay additional rent ΔR or other alternative compensations to the owner when he does not want to cooperate in green retrofit during the contract period. To sum up, regardless of the occupier's initiative to implement green retrofit, green retrofit is implemented only if the owner wants to.

The benefit and cost of green retrofit are similar in two conditions, but the difference is whether an increment exists in rent after retrofit. According to previous case studies, rent, price, and occupancy rate of a building are positively related to its green feature, as shown in Table 6.4. Therefore, this study assumes that green retrofit can raise building value (Miller and Buys, 2008), occupancy rate, and rent (Thomas, 2010). The key information can be summarized as follows:

$$\mathrm{S}_{e11}^{so} + \Delta P_{11}^{so} - D_{11}^{so} \approx \mathrm{S}_{e12}^{so} + \Delta P_{12}^{so} - D_{12}^{so} \ , \ \ \Delta R_{oc11}^{so} \geq 0 \ . \tag{2}$$

Referring to these data for the formula in Figure 6.2, the matrix reveals that

$$\mathrm{S}_{e11}^{so} + \Delta P_{11}^{so} - D_{11}^{so} - \Delta R_{oc11}^{so} \leq \mathrm{S}_{e12}^{so} + \Delta P_{12}^{so} - D_{12}^{so} , \tag{3}$$

or

$$\mathrm{B}_{oc11}^{so} \leq \mathrm{B}_{oc12}^{so} \ . \tag{4}$$

Table 6.4 Premium of rent, value, and occupancy rate in green buildings

Literature	Rental Premium	Value Premium	Occupancy Rate Premium
Miller et al. (2008)	9%	No Premium	2%–4%
Eichholtz et al. (2010)	3.3%	1.9%	NA
Pivo and Fisher (2010)	2.7%	8.5%	NA
Wiley et al. (2010)	7%–17%	NA	10%–18%
Fuerst and McAllister (2011)	4%–5%	25%–26%	1%–3%

Formula (4) indicates that the occupier should choose "reluctant to retrofit" or non-cooperation if the owner has the initiative to implement green retrofit.

The action of the occupier when the owner is reluctant to retrofit

If both the owner and the occupier are reluctant, then the building will operate without the innovation. Thus, neither cost nor profit exists according to green retrofit, that is, $B_{oc22}^{so} = 0$. In the situation where the owner is reluctant and does not want to invest but the occupier is active in sustainable development, the occupier can choose to invest in the retrofit project. The single occupier is mainly a large organization that has high economic strength to support green retrofit (Miller and Buys, 2008). In addition to economic strength, the single occupier generally has a long rental contract, which makes reaping returns on investment possible to cover the retrofit cost. However, the costs of retrofit, which are investment I_{21}^{so} and disturbance of business during retrofit D_{21}^{so}, are short term and definite, whereas the profits of retrofit, which are energy cost saving S^{so}_{e21} and public impact ΔP^{so}_{21}, are long term and uncertain. Energy saving S^{so}_{e21} is also not reliable because of the contract period. The rental contract may be terminated in several years, which means the occupier can only obtain S^{so}_{e21} for several years rather than for the whole life cycle of a building. Specifically, the duration of reaping profit may be shorter than the payback time. Given that most investors are often reluctant to take challenges (Rhoads, 2010), they tend to assign more weight to certain costs in the short term than to uncertain profits in the long term. The key information can be summarized as follows:

$$S^{so}_{e21} + \Delta P^{so}_{21} - D^{so}_{21} - I^{so}_{21} \leq 0\,,\ \ B^{so}_{oc22} = 0\,. \tag{5}$$

That is, $B^{so}_{oc21} \leq B^{so}_{oc22}$. (6)

According to Formula (6), the occupier should choose "reluctant to retrofit" when the owner is reluctant to green retrofit because of the risk in payback period.

Formulas (4) and (6) suggest that the best interests of the occupier are served by the "reluctant to retrofit" action regardless of the action the owner takes; thus, "reluctant to retrofit" is the dominant strategy for the occupier (Myerson, 2013). The action of the owner based on the situation where the occupier is reluctant to retrofit is discussed in the following section.

The action of the owner when the occupier is reluctant to retrofit

As mentioned earlier, if the owner and the occupier are reluctant to green retrofit, then green retrofit will not be implemented, and the owner will obtains neither cost nor profit, such that $\mathrm{B}_{ow22}^{so}=0$. If the occupier is not interested in green retrofit but the owner has the initiative in the approach, then green retrofit can be implemented without the cooperation of the occupier, as discussed in the previous section. Under this condition, the owner cannot reap certain and direct payback from increased rent ΔR, but can only obtain uncertain, long-term, and indirect profits from green retrofit, such as operation cost saving S_{o12}^{so}, building value increase ΔV_{12}^{so}, and public impact ΔP_{12}^{so}. By contrast, investment I_{12}^{so} and coordination cost C_{c12}^{so} are certain, short-term, and direct, and are thus considered important by the owner because of their risk-adverse characteristic (Rhoads, 2010). The key information can be summarized as follows:

$$\mathrm{S}_{o12}^{so}+\Delta V_{12}^{so}+\Delta P_{12}^{so}-\mathrm{I}_{12}^{so}-C_{c12}^{so}\leq 0,\ \ \mathrm{B}_{oc22}^{so}=0\ . \tag{7}$$

That is, $\mathrm{B}_{ow12}^{so}\leq \mathrm{B}_{ow22}^{so}$ (8)

According to Formula (8), the owner should choose “reluctant to retrofit” when the occupier is reluctant to green retrofit.

The preceding analysis in Formula (8) reveals that, in a single-occupied building, the occupier chooses “reluctant to retrofit” regardless of what the owner chooses, and the owner is reluctant to retrofit to guarantee his interests. Hence, the Nash equilibrium for the owner and the single occupier is “reluctant to retrofit” and “reluctant to retrofit” respectively. Given that a multi-occupied building is another common occupancy type, a comparative study is discussed in Section 6.2.4.

6.2.4 Retrofit decision for multi-occupied building

Given that each occupier is an independent economic entity in this scenario, the owner must play games with each occupier individually. The occupiers have similar scales, costs, and benefits, and so their decisions should not be significantly different. Therefore, occupiers are considered homogeneous in the game. The game can be abstracted with two players, namely, owner and homogeneous occupiers. This study does not focus on the differences of occupiers. The cooperation and games among occupiers are not included as well. The buildings jointly occupied by owners and tenants are more complex. Owners of buildings have both attributes of owners and tenants. The conditions inside joint ownership are also different, depending on the percentage of owner's ownership. For example, an owner occupied majority of a building is different from an owner occupied only minority of a building. Therefore, the joint ownership is not considered in the discussion of three scenarios this study.

Different from single-occupied condition, numerous occupiers exist in a multi-occupied building. In this condition, occupancy is relatively small scale and has a high turnover rate. Therefore, the owner is dominant in the relationship. Occupiers are powerless in negotiation and can only choose to "vote with their feet," which means relocating to another building. Relocation raises additional costs for occupiers and owner in terms of relocation cost and turnover cost respectively. Table 6.5 describes these additional costs.

Table 6.5 Decision variables in multi-occupied buildings

Stakeholder	Variable	Definition	Driver/Barrier
Owner	C_t	turnover cost of owner	B_{OW}1/4
Occupier	C_r	relocation cost of occupier	B_{OC}6

The other advantages and disadvantages of green retrofit are similar to those of the condition of single-occupied building. The payoff matrix for owners and occupiers in multi-occupied buildings is shown in Figure 6.3, where the superscript "*mo*" represents the multi-occupied condition.

Occupiers

Owner	Initiative to retrofit	Reluctant to retrofit
Initiative to retrofit	$B^{mo}_{ow11}=S^{mo}_{o11}+\Delta V^{mo}_{11}+\Delta R^{mo}_{ow11}+\Delta P^{mo}_{11}-I^{mo}_{11}-C^{mo}_{c11}$ $B^{mo}_{oc11}=S^{mo}_{e11}-D^{mo}_{11}-\Delta R^{mo}_{oc11}$	$B^{mo}_{ow12}=S^{mo}_{o12}+\Delta V^{mo}_{12}+\Delta R^{mo}_{ow12}+\Delta P^{mo}_{12}-I^{mo}_{12}-C^{mo}_{t12}-C^{mo}_{c11}$ $B^{mo}_{oc12}=-C^{mo}_{r12}$
Reluctant to retrofit	$B^{mo}_{ow21}=-C^{mo}_{t21}$ $B^{mo}_{oc21}=-C^{mo}_{r21}$	$B^{mo}_{ow22}=0$ $B^{mo}_{oc22}=0$

Figure 6.3 Payoff matrix for owner and occupier in multi-occupied buildings

On the basis of this adapted matrix, the following scenarios can be investigated to identify the Nash equilibrium under the multi-occupied condition.

The action of the owner when the occupier has the initiative to retrofit

In a situation where the owner does not want to invest on retrofit but the occupiers want to, a single occupier does not have enough economic capabilities or influential power to implement the approach. Therefore, if the active occupiers cannot reach consensus with the reluctant owner and cannot implement retrofit by themselves, they can only choose to "vote with their feet," which raises the turnover cost for the owner C_{t21}^{mo}. However, this turnover cost does not increase significantly because small companies consider cost and location as the dominant factors for building selection (Rhoads, 2010). If occupiers are interested in green retrofit, then they will support it and pay additional rent to the owner as compensation for the additional costs (Fuerst and McAllister, 2011). Under this condition, the owner can reap a direct payback from the increased rent ΔR_{ow11}^{mo} as compensation for the investment. However, the owner must pay the coordination cost to raise the rent. Coordination cost C_{c11}^{mo} is proportional to the number of occupiers. This cost is very high when numerous occupiers, various contracts, and different rental periods exist (Rhoads, 2010), namely, $\mathrm{C}_{c11}^{mo} >> 0$. The key information can be summarized as follows:

$$\mathrm{S}_{o11}^{mo} + \Delta V_{11}^{mo} + \Delta R_{ow11}^{mo} + \Delta P_{11}^{mo} - \mathrm{I}_{11}^{mo} - \mathrm{C}_{c11}^{mo} \leq 0, \quad -\mathrm{C}_{t21}^{mo} \approx 0 \tag{9}$$

That is, $$\mathrm{B}_{ow11}^{mo} \leq \mathrm{B}_{ow21}^{mo} \tag{10}$$

Formula (10) indicates that the owner should choose "reluctant to retrofit" when the initiative of the occupiers is to engage in green retrofit.

The action of the owner when the occupier is reluctant to retrofit

If both owner and occupiers are reluctant to green retrofit, then green retrofit is not implemented. The owner obtains neither cost nor profit, such that $\mathrm{B}_{ow22}^{mo} = 0$. When the occupier is not active in green retrofit but the owner is, the approach can be implemented without the cooperation of some reluctant occupiers. If some occupiers cannot reach consensus with the owner, they will move out, which results in turnover cost C_{t12}^{mo} for the owner. Generally, occupancy rate and rent per unit increase after green retrofit (Ma et al., 2012; Thomas, 2010). Thus, even though some occupiers move out because of retrofit, the owner can reap increased rent $\Delta\mathrm{R}_{ow12}^{mo}$ from the new occupiers. High occupancy rate in the future and high rent from a new occupier are indirect and long-term benefits for the owner. Other profits of retrofit, including operation cost saving S_{o12}^{mo}, increased building value ΔV_{12}^{mo}, and public impact ΔP_{12}^{mo}, are long term and uncertain. By contrast, the costs of retrofit are short term and definite. The risk-adverse investor does not want to take the challenge of comparing uncertain interests with specific costs. The key information can be summarized as follows:

$$\mathrm{S}_{o12}^{mo} + \Delta V_{12}^{mo} + \Delta\mathrm{R}_{ow12}^{mo} + \Delta P_{12}^{mo} - \mathrm{I}_{12}^{mo} - \mathrm{C}_{t12}^{mo} - C_{c12}^{mo} \leq 0, \quad \mathrm{B}_{ow22}^{mo} = 0 \tag{11}$$

That is, $\mathrm{B}_{oc12}^{mo} \leq \mathrm{B}_{oc22}^{mo}$. (12)

According to Formula (12), the owner should choose “reluctant to retrofit” when the occupier is reluctant to green retrofit.

Formulas (10) and (12) suggest that the best interests of the owner are served by the “reluctant to retrofit” action regardless of the action occupiers take, and thus “reluctant to retrofit” is the dominant strategy for the owner (Myerson, 2013). The action of the occupiers based on the situation where the owner is reluctant to retrofit is discussed in the following section.

The action of the occupier when the owner is reluctant to retrofit

If both owner and occupier are reluctant to green retrofit, then the building will be operated without green retrofit. Thus, neither cost nor profit exists according to green retrofit, such that $\mathrm{B}_{oc22}^{mo} = 0$. If occupiers want to implement green retrofit but the owner does not, the approach will not be implemented, and the active occupiers will move out, which will incur a relocation fee C_{r21}^{mo}. The key information can be summarized as follows:

$$\mathrm{S}_{e21}^{so} + \Delta P_{21}^{so} - D_{21}^{so} - I_{21}^{so} \leq 0 , \quad \mathrm{B}_{oc22}^{mo} = 0 \tag{13}$$

That is, $\mathrm{B}_{oc21}^{so} \leq \mathrm{B}_{oc22}^{so}$ (14)

Formula (14) indicates that the occupier should choose “reluctant to retrofit” when the owner is reluctant to green retrofit.

On the basis of the above analysis, the Nash equilibrium for the owner and the occupiers under the multi-occupied condition is “reluctant to retrofit” and “reluctant to retrofit” respectively. This conclusion is consistent with two cases in China, which were studied through interviews conducted in October 2014. One case is the Jin Bin Teng Yue Building, an office building in Guangzhou, China. The building is occupied by about 400 tenants. The owner had the initiative to implement energy-efficient lighting in public areas. The negotiation with the tenant committee and tenants with opposing opinions took almost half a year. The facility managers complained that despite the small scale of this green retrofit project, coordinating required from them a considerable amount of time. The other case is the Electronic Technology Building in Shenzhen, China, which is a commercial building used for the wholesale selling of electronic products. The building has more than 1000 tenants, many of whom occupy areas less than 10 m^2. This building has yet to be green retrofitted. The facility managers stated they had considered green retrofit but had to give up the idea because coordinating more than 1000 tenants was extremely difficult.

6.2.5 Discussion

Under the owner-occupied condition, owners can decide by themselves based on Formula (1). However, under the single- and multi-occupied conditions, the Nash equilibrium is "reluctant to retrofit" and "reluctant to retrofit" owing to the interaction between the owners and tenants at the initial phase. Such reluctance explains the lack of enthusiasm for green retrofit in the industry. Figure 6.4 illustrates the mechanism of game theory analysis under different occupancy types. The major reasons and issues are discussed below.

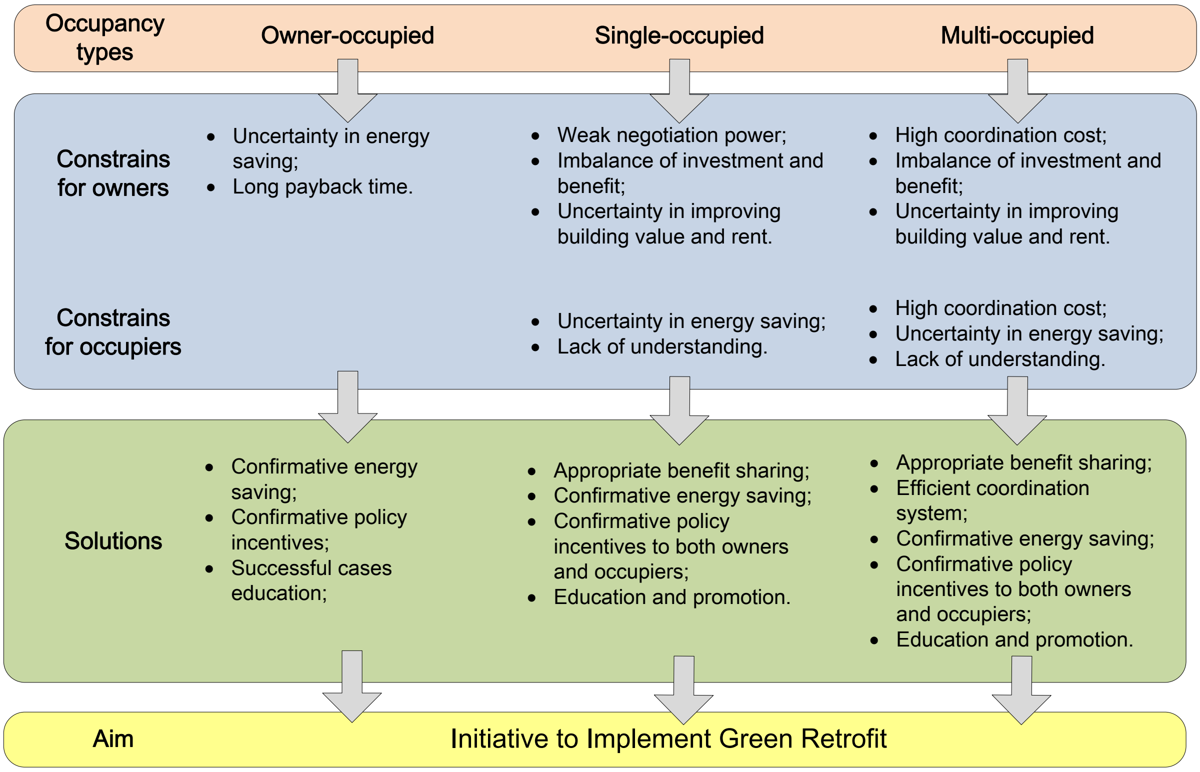


Figure 6.4 Mechanism of game theory analysis under different occupancy types

Differences among occupancy types

The difficulty level of green retrofit is strongly related to the occupancy type of a building. First, the compensation of investment on green retrofit varies according to different occupancy types. In owner-occupied buildings, owners can obtain benefits directly from the green retrofit through low energy consumption. However, in single- or multi-occupied buildings, the investment of owners in green retrofit will not guarantee direct energy savings. In these conditions, the owners may be rewarded primarily in three other ways, namely, higher rents, lower holding costs, and lower risk (Fuerst and McAllister, 2011), compared to owner-occupied buildings. Retrofit benefits are transferred via the first way from tenants to owners. In other words, the green retrofit projects are partly and indirectly funded by the occupiers. The second way, lower holding costs, refers to lower maintenance cost and longer operation time until the next retrofit. The last way involves avoiding premature obsolescence, policy changing, and risk associated with the future increase in energy cost. Among these three rewarding ways, higher rents may be the most direct and promising way to cover costs and earn profits. Risk is difficult to quantify. Low holding cost may not be realized because of new technologies and human maintenance behaviors during long operation periods. Thus, if the owners cannot obtain direct energy-saving benefits, then they will pursue higher rents or other kinds of direct economic compensation from the occupants. In single-occupied buildings, the single occupier is generally a large organization that has a long rental contract. If the occupier is reluctant to retrofit, raising rent ΔR_{ow}^{so} in the short term after retrofit will be difficult. In multi-occupied buildings, the occupiers are relatively small scale and have short-term contracts with owners. Hence, owners can raise rent ΔR_{ow}^{mo} to compensate for the retrofit cost in the short term.

Second, the coordination cost of green retrofit relies on occupancy type. Coordinating with occupiers about the green retrofit decision takes time and incurs labor and economic costs on the part of the owners. Coordination cost C_c is positively related to the number of occupiers N_{oc}, that is, $C_c \propto N_{oc}$. In owner-occupied buildings, owners do not need to coordinate with occupiers, and thus $C_c = 0$. In single-occupied buildings, negotiations are conducted with only one occupier. Therefore, the coordination cost is low, that is, $C_c \approx 0$. In multi-occupied buildings, however, coordination cost is high enough to be emphasized, that is, $C_c >> 0$, because there are numerous occupiers with various contracts, which increases the difficulty of negotiating.

Third, the occupancy rate, turnover cost of the owner, and relocation cost of the occupier are different among occupancy types. In the owner-occupied condition, owners do not need to consider the occupancy rate and turnover cost, that is, $C_t = 0$. In the single-occupied condition, the single occupier affects the occupancy rate considerably. If the single occupier moves out, then the turnover cost will be high for the owner and the relocation cost will be high for the occupier, that is, $C_t >> 0, C_r >> 0$. Therefore, the single occupier has a strong negotiating power and will not choose to terminate the contract even if his opinion differs from that of the owner. In the multi-occupied condition, turnover and relocation costs are much lower than those in the single-occupied condition. From the long-term perspective, the occupancy rate can be improved by green retrofit (Fuerst and McAllister, 2011), which will also raise the rent.

Split incentives between owners and tenants

Owners and tenants are most likely to have conflicting opinions on green retrofit decisions, because the former usually invests in green retrofit projects, but the various benefits (e.g., energy saving, health, and productivity improvement, etc.) will be reaped by the latter. This imbalance between investment and benefit, which hinders cooperation between owners and tenants, is an essential problem in green retrofit decisions.

Green retrofit projects can be invested in three ways, namely, 1) owner funded, 2) tenant funded, and 3) third-party financing (Rhoads, 2010). The third situation is related to external influence, which is not considered in this study. Occupiers may not stay in one building for a long time, which makes investments in green retrofit projects risky. Hence, owner funding is the primary financing type in practical green retrofit projects, except when the tenant has enough economic capability and a long rental contract.

Green retrofit is supposed to improve energy efficiency and save energy cost. Who benefits from cost savings is related to the type of rental contract. “Net rental contract” indicates that tenants pay the energy bill and will benefit from energy savings. “Gross rental contract” indicates that owners pay the energy bill and will benefit directly from energy savings. The former is more common than the latter because it can result in low operating costs (Fuerst and McAllister, 2011). Clearly, based on net rental contracts, the primary beneficiary of green retrofit is the tenant who pays the energy bills. When a building is not owner-occupied, this benefit, however, cannot provide direct incentives that can motivate an owner to invest in green retrofit projects.

Several cases have demonstrated that owners and tenants stand at different points with regard to split incentives and interest conflicts. Menassa and Baer (2014) conducted a case study of a bachelor quarters building at Naval Station Great Lakes in the US. Although both the owner and tenants belong to US government, their results indicated that the priorities in retrofit requirements are significantly different between owners and tenants. The difference rate ranges from -36% to 76%. Even if the tenants are also public organizations, they also have interest conflicts with the owner of the building, since the public organizations are independent from economic perspective. Table 6.6 summarizes the most different requirements. Given these split incentives, an appropriate investment and return distribution system is highly needed for green retrofit promotion (Fuerst and McAllister, 2011).

Table 6.6 Difference of green retrofit requirements between tenants and owners

Requirements	**Rating of tenants**	**Rating of owners**	**Difference**
Reduce costs of carbon offset	3	1.7	76%
Leverage business platforms	3.8	2.2	73%
Improve occupant health	4.3	3	43%
Improve occupant attendance	4.2	3	40%
Avoid costs due to opposition	2.8	2	40%
Lower project capital costs	2.7	4.2	-36%

Source: Menassa and Baer (2014)

Uncertainty of green retrofit

Another essential issue for green retrofit is uncertainty, which can be analyzed from the following perspectives. First, although numerous studies have emphasized that green retrofit will improve energy efficiency (Caccavelli and Gugerli, 2002; Mickaityte et al., 2008; Rey, 2004), others have forwarded opposing opinions. Newsham et al. (2009) indicated that 28%–35% of energy-certified buildings use more energy than their conventional counterparts. Scofield (2009) also found that the energy savings of certified buildings are not significantly different from those of comparable buildings. Thus, after green retrofit, and even with certification as LEED, realizing energy savings in operation remains uncertain, such that $\mathrm{S}_e - D - I \square\ 0$. This finding implies that owners and tenants may not obtain a direct benefit from retrofit.

Second, other researchers have questioned the opinion that green retrofit will increase building value (Miller and Buys, 2008) and occupancy rate (Fuerst and McAllister, 2011). Many organizations lack an understanding of or interest in the environment (Davies and Osmani, 2011), especially small organizations that consider location and cost as the most dominant factors in building selection rather than sustainable factors. On the basis of this analysis, green retrofit may result in a higher rent, which may reduce the occupancy rate. Thus, realizing higher building value and occupancy rate after green retrofit is uncertain. Although green retrofit can achieve positive results in relation to building value and occupancy rate, calculating the results quantitatively is difficult because of various influencing factors (Rhoads, 2010).

Third, most owners and tenants lack experience in and understanding of green retrofit (Davies and Osmani, 2011; Kasivisvanathan et al., 2012), including its processes (Ali et al., 2008), available technologies (Miller and Buys, 2008), and information on existing buildings (Menassa, 2011). Additionally, green retrofit involves more complex design analysis, more intense interdisciplinary collaboration (Lapinski et al., 2006), and more stakeholders (Davies and Osmani, 2011) than regular retrofit. These factors may intensify uncertainty in decision making on green retrofit.

Last, the payback period of green retrofit is relatively long (Kasivisvanathan et al., 2012; Menassa, 2011). In a long payback period, numerous uncertain factors may affect the success of green retrofit, such as related polices, interest rate, technology progress, and environmental change. These uncertain factors may cause decision-makers to be more cautious and bring negative influences to the green retrofit project.

6.3 Game Model with Government Incentives

6.3.1 Problem definition

In Section 6.2, the interest relationship between owners and tenants are analyzed based on the game model. The results indicate that both owners and tenants are reluctant to green retrofit without government incentives, as shown at the top of Figure 6.5. This reluctance explains why most buildings do not respond to the promotion of green retrofit in reality. The social welfare and environmental benefits of green retrofit are not considered as high priority by individuals. Thus, the government needs to give incentives to balance the benefit and cost and promote green retrofit through an economic lever.

The interest relationship among stakeholders when the government joins the game is shown at the bottom of Figure 6.5. The government evaluates the environmental benefits and social welfare of a green retrofit project, shown by the green line in Figure 6.5, and gives incentives to the owner of the building accordingly, shown by the red line in Figure 6.5. The government incentives will increase the owner's benefit from green retrofit. If the incentives are high enough, the owners will take the initiative to green retrofit. If a building is not owner-occupied, the owner has to negotiate with the tenants and give them incentives to balance the benefit of green retrofit, shown by the dashed red line in Figure 6.5.

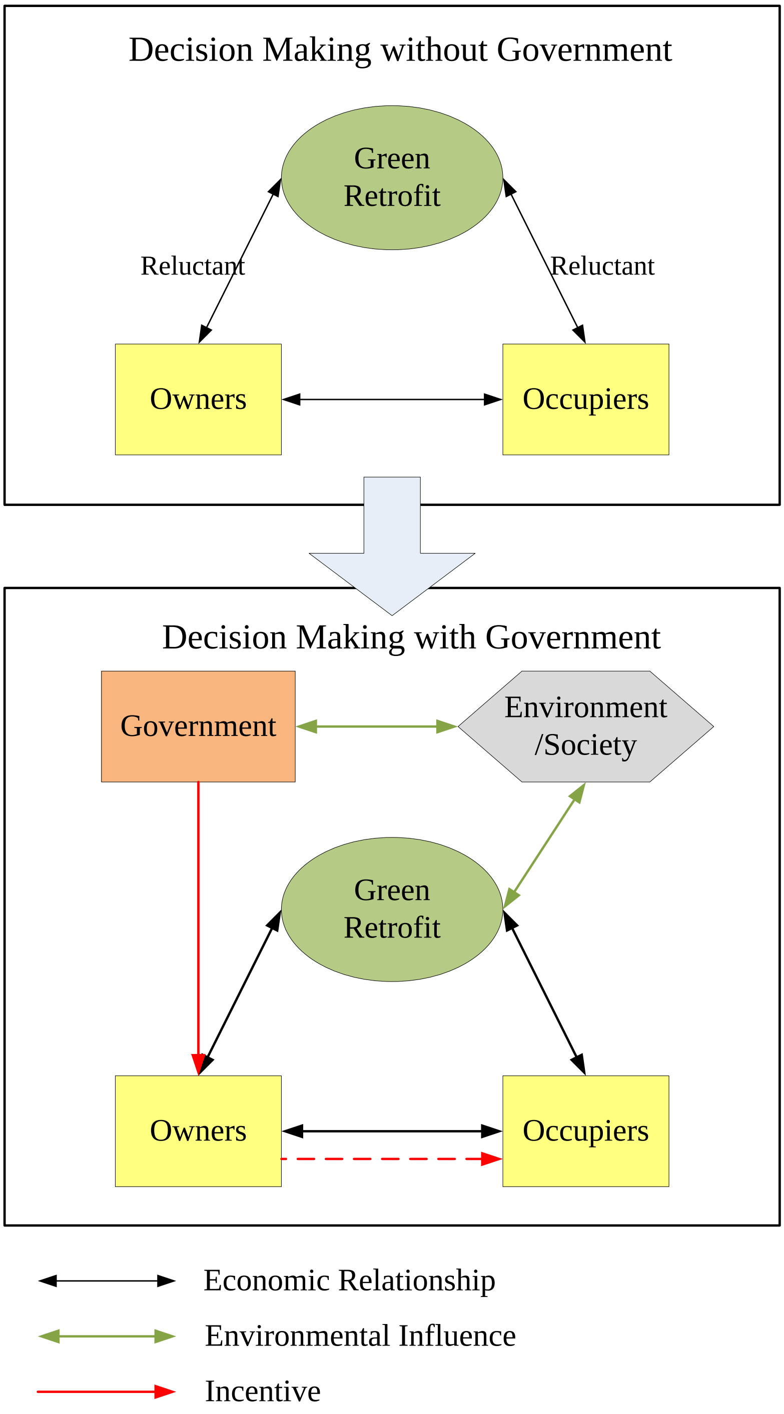


Figure 6.5 Interest relationship of stakeholders in green retrofit

The costs and benefits of stakeholders are listed in Table 6.7. The benefits of owners are economic benefits from the retrofit and incentives from the government, while the costs of owners are the cost of green retrofit and incentives to tenants. The benefits of tenants are economic benefits from the retrofit and incentives from owners, while the costs of tenants are the cost of green retrofit. The benefit of government is the environmental and social benefits, while the cost is the incentives to owners. The incentive from owners to tenants is optional, depending on the relationship between them.

Table 6.7 Costs and benefits of stakeholders with government incentives

Stakeholders	Benefits	Costs
Owners	Economic benefits from retrofit	Cost of green retrofit
	Incentives from government	Incentives to tenants (optional)
Tenants	Economic benefits from retrofit	Cost of green retrofit
	Incentives from owners (optional)	
Government	Environment and social benefit	Incentives to Owners

The problem in this section is determining how to maximize the efforts of owners and tenants for green retrofit. To achieve the maximized effort, how much incentive should be given by the government should be calculated and the optimal balance among three stakeholders (i.e., owners, tenants and government) should be identified. The principal–agent model will be adopted to solve this problem, and the details of deviations will be illustrated in the next section.

6.3.2 Incentive analysis and optimal actions of stakeholders

According to the occupied type and whether owners benefit from green retrofit, four quadrants can be divided, shown in Figure 6.6.

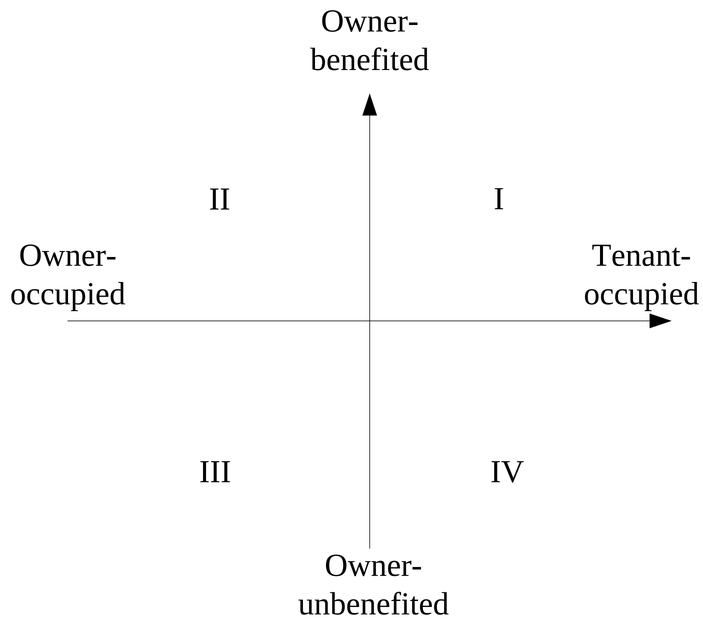


Figure 6.6 Four quadrants of buildings in green retrofit

Quadrant I: represents the tenant-occupied and owner-benefited buildings, normally the commercial buildings where the owners pay the utility bills.

Quadrant II: represents the owner-occupied and owner-benefited buildings, normally the headquarters of companies and institutes. The owners of these types of buildings occupy the buildings and pay the utility bills themselves, and so they can gain benefits from green retrofit by saving on energy costs.

Quadrant III: represents the owner-occupied and owner-unbenefited buildings, normally government and public buildings. The owners of these types of buildings occupy the buildings, but the utility bills are paid by public finance. Hence, the benefits of green retrofit belong to public finance rather than to the building owners.

Quadrant IV: represents the tenant-occupied and owner-unbenefited buildings, normally the commercial buildings where the tenants pay the utility bills. Most commercial buildings, including office buildings and shopping centers, are in this quadrant.

The variables in the game model analysis among owners, tenants, and government are listed in Table 6.8. Four types of variables exist, namely, owner, tenant, government, and environment. The variables of the first three types belong respectively to each stakeholder; that is, these variables are directly related to the stakeholders. The variables of the environment type depend on the environmental situation rather than the stakeholders. For example, the exogenous uncertainty probability distribution θ depends on climate, condition of the existing building, technology development, and so forth. It cannot be changed by the stakeholders, and is thus defined as an environment variable. k_{ec} and k_{en} are coefficients of the economic and environmental benefits from green retrofit respectively. They mainly depend on technology development and the system to retrofit (e.g., HVAC system, lighting system, windows). In a certain time and for a certain system, the energy efficient improvement by green retrofit is at a certain level.

Table 6.8 Variables of the game model among owners, tenants, and government

Type	Variable	Definition
Owner	a^o	owners' effort to green retrofit
	c^o	cost of owners' effort to green retrofit
	ω^o	owners' income from green retrofit
	s^o	incentive of owner to tenant
	U^o	utility function of owners
Tenant	a^t	tenants' effort to green retrofit
	c^t	cost of tenants' effort to green retrofit
	ω^t	tenants' income from green retrofit
	U^t	utility function of tenant
Government	s^g	incentive of government to owners
	U^g	utility function of government
Environment	θ	exogenous uncertainty probability distribution, mean is 0, variance is σ
	k_{ec}	coefficient of economic benefit from green retrofit, $k_{ec} \geq 0$
	k_{en}	coefficient of environmental benefit from green retrofit, $k_{en} \geq 0$
	π	benefit of green retrofit, $\pi=\pi_{ec}+\pi_{en}$
	π_{ec}	economic benefit of green retrofit
	π_{en}	environmental benefit of green retrofit

On the basis of the aforementioned problem definition, the relation among owners, tenants, and government can be analyzed with the principal–agent theory. The most efficient incentive can be identified and the optimal actions of each stakeholder can be proposed accordingly. The derivations and results are illustrated in the following section.

Quadrant II: owner-occupied and owner-benefited

In Quadrant II, only owners occupy buildings and there is no tenant. The economic benefit of green retrofit π_{ec} depends on the efforts of owners $k_{ec}a^o$ and exogenous uncertainty θ. θ indicates the uncertainty of exogenous environment (e.g., climate changes, technology development). π_{ec} can be calculated by Equation (15):

$$\pi_{ec} = k_{ec}a^o + \theta \quad (15)$$

Similarly, the environmental benefit of green retrofit π_{en} depends on the efforts of owners $k_{en}^o a^o$ and exogenous uncertainty θ. Thus, π_{en} can be calculated by Equation (16):

$$\pi_{en} = k_{en}^o a^o + \theta \quad (16)$$

Incentives are offered by the government to promote green retrofit for existing buildings. To encourage owners to pay more efforts on green retrofit and achieve better effect, the incentives have a positive correlation with the environmental benefit of green retrofit π_{en}. Owing to exogenous uncertainty, even when owners pay efforts to green retrofit, the effect may not be positive. Therefore, a constant α^o is defined to ensure the incentive policy is optimal to the exogenous uncertainty. This linear incentive contract is shown in Equation (17). β^o is the coefficient of the incentive, which indicates the redistribution of benefits from green retrofit. The higher the β^o, the more incentives the government will give for the same green retrofit results. Specifically, the owners can get more benefits from green retrofit, while the government gets less benefit from green retrofit.

$$s^g = \alpha^o + \beta^o \pi_{en} . \tag{17}$$

Assuming the government is risk neutral, the utility function of the government is the environmental benefits from green retrofit minus the incentives to owners, shown in Equation (18).

$$U^g = \pi_{en} - s^g . \tag{18}$$

The certainty equivalent of the government is the expectation of government utility, shown in Equation (19).

$$E(U^g) = E(\pi_{en} - s^g) . \tag{19}$$

By substituting Equations (16) and (17) into (19), Equation (19) can be transformed into

$$\begin{aligned} E(U^g) &= E(\pi_{en} - \alpha^o - \beta^o (k_{en}^o a^o + \theta)) \\ &= -\alpha^o + (1-\beta^o) k_{en}^o a^o \end{aligned} . \tag{20}$$

For the building owners who carry out green retrofit, their incomes ω^o can be defined as the economic benefits from green retrofit (e.g., energy cost savings, building value increasing) plus government incentives minus the costs of green retrofit, shown in Equation (21).

$$\omega^{o}=\pi_{ec}+s^{g}-c^{o} \quad (21)$$

Let $c^{o}=\frac{1}{2}b^{o}a^{2}$,

Equation (21) can be transformed into

$$\omega^{o}=k_{ec}^{o}a^{o}+\theta+\alpha^{o}+\beta^{o}(k_{en}^{o}a^{o}+\theta)-\frac{1}{2}b^{o}a^{2}, \quad (22)$$

where b^{o} is the coefficient of cost. The higher the b^{o}, the greater the costs for the same effort. Furthermore, the cost function is a convex function, which means marginal cost increases with effort; that is, marginal efficiency decreases when effort increases.

Assuming the owner is risk averse and has a constant absolute risk aversion, the utility function of owners is

$$U^{o}=-e^{\rho\omega}, \quad \rho=-\frac{U^{o\prime\prime}}{U^{o\prime}} . \quad (23)$$

where ρ is the constant absolute risk aversion, which indicates the degree of risk aversion. The higher the value of ρ, the higher the risk aversion the owners have.

The certainty equivalent of owners is the expectation of income minus risk premium $\frac{1}{2}\rho\beta^{o2}\sigma^{2}$, which is the risk cost of owners. The higher the $\frac{1}{2}\rho\beta^{o2}\sigma^{2}$, the higher the risk cost the owners have. The expected utility of owners is shown in Equation (24).

$$
\begin{aligned}
E(U^o) &= E(\omega^o) - \frac{1}{2}\rho\beta^{o2}\sigma^2 \\
&= E(k_{ec}^o a^o + \theta + \alpha^o + \beta^o(k_{en}^o a^o + \theta) - \frac{1}{2}b^o a^{o2}) - \frac{1}{2}\rho\beta^{o2}\sigma^2 \quad . \qquad (24) \\
&= k_{ec}^o a^o + \alpha^o + \beta^o k_{en}^o a^o - \frac{1}{2}b^o a^{o2} - \frac{1}{2}\rho\beta^{o2}\sigma^2
\end{aligned}
$$

If the information is complete, meaning the government has all the owner information, then the government can give incentives based on the efforts of owners. To achieve optimal results, the government can induce certain efforts of owners through policies and laws. However, in reality, owner information is incomplete, which means the government does not know how many efforts the owner pays on green retrofit. As rational entities, owners always choose the strategy that maximizes their interests rather than satisfies government expectation. The government cannot force owners' efforts, only induce the expected efforts by an economic lever.

Under the incomplete information, the government faces the problem of how to choose the most efficient incentive to induce the efforts of owners for green retrofit and optimize government utility. This problem can be mapped into a principal–agent model, and the mathematical expression is shown in Equation (25).

$$\max_{\alpha^o,\beta^o,a^o} E(U^g) = \max_{\alpha^o,\beta^o,a^o} (-\alpha^o + (1-\beta^o)k_{en}^o a^o) \qquad (25)$$

s.t.

(IR): $E(U^o) \geq \omega_0^o$

(IC): $a^o = \dfrac{k_{ec}^o + \beta^o k_{en}^o}{b^o}$.

The individual rationality (IR) constrain means the certainty equivalent of owners' incomes $E(U^o)$ should be greater than the opportunity cost of efforts ω_0^o. The incentive compatibility (IC) constrain means that, under a certain incentive, owners will choose an effort of green retrofit to maximize their interests, that is, $\frac{\partial E(U^o)}{\partial a^o}=0$.

Therefore, $a^o = \frac{k_{ec}^o + \beta^o k_{en}^o}{b^o}$.

The optimal incentive coefficient β^o and the intercept α^o can be calculated by solving the optimization problem defined by Equation (26).

$$\beta^o = \frac{k_{en}^{o\,2}}{b^o \rho\sigma^2 + k_{en}^{o\,2}} \tag{26}$$

$$\alpha^o = \omega_0 + \frac{1}{2}\rho\beta^{o2}\sigma^2 - \frac{(k_{ec}^o + \beta k_{en}^o)^2}{2b^o}.$$

Quadrant III: owner-occupied and owner-unbenefited

Both Quadrants II and III are owner-occupied, but the difference between them is whether the owner can get economic benefits from green retrofit. Therefore, the income of the owner from green retrofit is the government incentive minus the cost of green retrofit, shown in Equation (27).

$$\omega^o = s^g - c^o \quad . \tag{27}$$

Substituting Equation (17) into (27) can transform Equation (27) into

$$\omega^o \; = \alpha^o + \beta^o (k_{en}^o a^o + \theta) - \frac{1}{2} b^o a^2 \quad . \tag{28}$$

The certainty equivalent of owners is the expectation of income minus risk premium $\frac{1}{2}\rho\beta^{o2}\sigma^2$, which is the risk cost of owners. The expected utility of owners is shown in Equation (29).

$$\begin{aligned} E(U^o) &= E(\omega^o) - \frac{1}{2}\rho\beta^{o2}\sigma^2 \\ &= E(\alpha^o + \beta^o(k_{en}^o a^o + \theta) - \frac{1}{2}b^o a^2) - \frac{1}{2}\rho\beta^{o2}\sigma^2 \ . \\ &= \alpha^o + \beta^o k_{en}^o a^o - \frac{1}{2}b^o a^2 - \frac{1}{2}\rho\beta^{o2}\sigma^2 \end{aligned} \tag{29}$$

Similar to Quadrant II, the problem of the government is how to choose the most efficient incentive to induce the efforts of owners for green retrofit and optimize the government utility. This problem can be mapped into a principal–agent model, and the mathematical expression is shown in Equation (30).

$$\max_{\alpha^o,\beta^o,a^o} E(U^g) = \max_{\alpha^o,\beta^o,a^o} (-\alpha^o + (1-\beta^o)k_{en}^o a^o) \tag{30}$$

s.t.

(IR): $E(U^o) \geq \omega_0^o$

(IC): $a^o = \dfrac{\beta^o k_{en}^o}{b^o}$.

The IR constrain means the certainty equivalent of owners' incomes $E(U^o)$ should be greater than the opportunity cost of efforts ω_0^o. The IC constrain means that, under a certain incentive, owners will choose an effort of green retrofit to maximize their interests, that is, $\dfrac{\partial E(U^o)}{\partial a^o}=0$. Therefore, $a^o = \dfrac{\beta^o k_{en}^o}{b^o}$.

The optimal incentive coefficient β^o and intercept α^o can be calculated by solving the optimization problem defined by Equation (31).

$$\beta^o = \frac{k_{en}^{o\,2}}{b^o \rho \sigma^2 + k_{en}^{o\,2}} \tag{31}$$

$$\alpha^o = \omega_0 + \frac{1}{2}\rho\beta^{o2}\sigma^2 - \frac{(\beta k_{en}^o)^2}{2b^o}.$$

Quadrant I: tenant-occupied and owner-benefited

Different from Quadrants II and III, Quadrant I is tenant-occupied, and so there are three stakeholders (i.e., government, owners, and tenants). The economic and environmental benefits of green retrofit depend on the efforts of both owners and tenants. If the tenants do not cooperate with the owners in green retrofit, the project may not succeed or may have low efficiency. Therefore, the efforts of both owners and tenants are important to the effect of green retrofit. The economic and environmental benefit of green retrofit can be defined respectively in Equations (32) and (33).

$$\pi_{ec} = k_{ec}(a^o + a^t) + \theta \tag{32}$$

$$\pi_{en} = k_{en}(a^o + a^t) + \theta. \tag{33}$$

In Quadrants II and III, the government is the principal and the owner is the agent. Besides the government and the owner, Quadrant I has another principal–agent relation, which is owner and tenant. Owing to the incomplete information, the government should give incentives to owners to induce their efforts. The incentive in Quadrant I by the government to the owners is the same as that in Quadrants II and III, as shown in Equation (17). Similarly, because of the incomplete information, owners should give tenants incentives to encourage their active involvement in green retrofit. The incentives by owners to tenants can be defined in Equation (34).

$$s^o = \alpha^t + \beta^t \pi_{ec} \quad . \tag{34}$$

The constant α^t is defined to ensure the incentive is optimal to the exogenous uncertainty. The β^t is the coefficient of the incentive; it indicates the redistribution of the benefits from green retrofit. The higher the β^t, the more incentives the owners will give for the same green retrofit results. Specifically, the tenants can get more benefit from green retrofit, while owners get less.

The incomes of owners from green retrofit can be defined as the economic benefit of green retrofit plus government incentives minus the incentives to tenants minus the cost of green retrofit, shown in Equation (35).

$$\omega^o = \pi_{ec} + s^g - s^o - c^o \quad . \tag{35}$$

The incomes of tenants from green retrofit can be defined as the incentives to tenants minus the cost of green retrofit, shown in Equation (36).

$$\omega^t = s^o - c^t \tag{36}$$

Assuming owners are risk neutral, the certainty equivalence of owners' utility is

$$E(U^o) = E(\omega^o) = E(\pi_{ec} + s^g - s^o - c^o) \quad . \tag{37}$$

Equation (37) can be transformed into

$$E(U^o) = \alpha^o - \alpha^t + k_{ec}(a^o + a^t) + \beta^o k_{en}(a^o + a^t) - \beta^t k_{ec} a^t - \frac{1}{2} b^o a^{o2} \quad . \tag{38}$$

Assuming tenants are risk averse, the certainty equivalence of tenants' utility is

$$\begin{aligned} E(U^t) &= E(\omega^t) - \frac{1}{2}\rho\beta^{t2}\sigma^2 \\ &= \alpha^t + \beta^t k_{ec} a^t - \frac{1}{2} b^t a^{t2} - \frac{1}{2}\rho\beta^{t2}\sigma^2 \end{aligned} \quad . \tag{39}$$

The problem of finding the optimal incentive strategy of the government–owner–tenant relationship can be decomposed into two steps: 1) the optimal strategy of owner and tenant is identified with the principal–agent model under a certain government incentive; and 2) based on the optimal strategy of owner and tenant from Step 1, the optimal strategy of the government can be solved with the principal–agent model.

In the principal–agent model of Step 1, the owners are principals and the tenants are agents. Owners do not know the efforts of tenants because of incomplete information, and thus incentives should be paid to tenants to induce their effort to green retrofit. The problem of the owner is how to choose the most efficient incentive to induce the efforts of tenants for green retrofit and optimize the owners' utility. This problem can be mapped into the principal–agent model, and the mathematical expression is shown in Equation (40).

$$\max_{\alpha^t,\beta^t,a^o,a^t} E(U^o) = \max_{\alpha^t,\beta^t,a^o,a^t} (\alpha^o - \alpha^t + k_{ec}(a^o + a^t) + \beta^o k_{en}(a^o + a^t) - \beta^t k_{ec} a^t - \frac{1}{2} b^o a^{o2})$$

(40)

s.t.

(IR): $E(U^t) \geq \omega_0^t$

(IC): $a^o = \dfrac{k_{ec} + \beta^o k_{en}}{b^o}$

$a^t = \dfrac{\beta^t k_{ec}}{b^t}$.

The IR constrain means the certainty equivalent of the tenants' incomes $E(U^t)$ should be greater than the opportunity cost of their efforts ω_0^t. The IC constrain means that under a certain incentive, owners and tenants will choose efforts of green retrofit to maximize their interests, namely, $\dfrac{\partial E(U^o)}{\partial a^o}=0$, $\dfrac{\partial E(U^t)}{\partial a^t}=0$. Therefore, $a^o = \dfrac{k_{ec} + \beta^o k_{en}}{b^o}$ and $a^t = \dfrac{\beta^t k_{ec}}{b^t}$.

The optimal incentive coefficient β^t can be calculated by solving the optimization problem defined by Equation (41).

$$\beta^t = \frac{k_{ec}^2 + \beta^o k_{en} k_{ec}}{k_{ec}^2 + \rho\sigma^2 b^t} \quad . \tag{41}$$

In Step 2, government knows the strategy of owners and tenants under a certain incentive of the government. The problem of the government is how to choose the most efficient incentive to induce the efforts of tenants and optimize the utility of the government. The mathematical expression of this problem is shown in Equation (42).

$$\max_{\beta^0} E(U^g) = \max_{\beta^0}(-\alpha^o + k_{en}(1-\beta^o)(a^o + a^t)) \tag{42}$$

s.t.

(IR): $E(U^t) \geq \omega_0^t$, $E(U^o) \geq \omega_0^o$

(IC): $a^o = \dfrac{k_{ec} + \beta^o k_{en}}{b^o}$

$$a^t = \frac{\beta^t k_{ec}}{b^t}$$

$$\beta^t = \frac{k_{ec}^2 + \beta^o k_{en} k_{ec}}{k_{ec}^2 + \rho\sigma^2 b^t}.$$

The optimal incentive coefficient β^o can be calculated by solving the optimization problem defined by Equation (43).

$$\beta^o = \frac{1}{2}[1 - \frac{k_{ec}}{k_{en}}] \tag{43}$$

Quadrant IV: tenant-occupied and owner-unbenefited

Both Quadrants I and IV are tenant-occupied, and so the economic and environmental benefits from green retrofit also depend on the efforts of both owners and tenants. The difference between them is whether the owner can get economic benefits from green retrofit. In Quadrant IV, owners cannot get economic benefits from green retrofit directly but can get incentives from the government. Owing to the incomplete information, owners should give tenants incentives to encourage their active involvement in green retrofit. Therefore, the income of the owner from green retrofit is the incentive from the government minus the incentive to tenants minus the cost of green retrofit, shown in Equation (44).

$$\omega^{o} = s^{g} - s^{o} - c^{o} \, . \tag{44}$$

The incomes of tenants from green retrofit can be defined as the economic benefit of green retrofit plus the incentives to tenants minus the cost of green retrofit, as shown in Equation (45).

$$\omega^{t} = \pi_{ec} + s^{o} - c^{t} \tag{45}$$

Assuming owners are risk neutral, the certainty equivalence of owners' utility is

$$E(U^{o}) = E(\omega^{o}) = E(s^{g} - s^{o} - c^{o}) \quad . \tag{46}$$

Equations (46) can be transformed into

$$E(U^{o}){=}\alpha^{o} - \alpha^{t} + \beta^{o} k_{en}(a^{o} + a^{t}) - \beta^{t} k_{ec} a^{t} - \frac{1}{2} b^{o} a^{o2} \quad . \tag{47}$$

Assuming tenants are risk averse, the certainty equivalence of tenants' utility is

$$\begin{aligned} E(U^{t}) &= E(\omega^{t}) - \frac{1}{2}\rho\beta^{t2}\sigma^{2} \\ &== \alpha^{t} + k_{ec}(a^{o} + a^{t}) + \beta^{t} k_{ec} a^{t} - \frac{1}{2} b^{t} a^{t2} - \frac{1}{2}\rho\beta^{t2}\sigma^{2} \end{aligned} \quad . \tag{48}$$

Similar to Quadrant I, the problem in Quadrant IV can be decomposed into two steps. In Step 1, the optimal strategy of owner and tenant is identified using the principal–agent model under a certain government incentive. The owners are principals and the tenants are agents. This problem can be mapped into the principal–agent model, and the mathematical expression is shown in Equation (49).

$$\max_{\alpha^t,\beta^t,a^o,a^t} E(U^o) = \max_{\alpha^t,\beta^t,a^o,a^t} (\alpha^o - \alpha^t + \beta^o k_{en}(a^o + a^t) - \beta^t k_{ec} a^t - \frac{1}{2} b^o a^{o2}) \qquad (49)$$

s.t.

(IR): $\alpha^t + k_{ec}(a^o + a^t) + \beta^t k_{ec} a^t - \frac{1}{2} b^t a^{t2} - \frac{1}{2}\rho \beta^{t2}\sigma^2 \geq \omega_0^t$

(IC): $a^o = \dfrac{\beta^o k_{en}}{b^o}$

$$a^t = \frac{k_{ec} + k_{ec}\beta^t}{b^t}.$$

The IR constrain means the certainty equivalent of tenants' incomes $E(U^t)$ should be greater than the opportunity cost of efforts ω_0^t. The IC constrain means that under a certain incentive, owners and tenants will choose efforts of green retrofit to maximize their interests, namely, $\dfrac{\partial E(U^o)}{\partial a^o}=0$, $\dfrac{\partial E(U^t)}{\partial a^t}=0$. Therefore, $a^o = \dfrac{\beta^o k_{en}}{b^o}$ and $a^t = \dfrac{k_{ec} + k_{ec}\beta^t}{b^t}$.

The optimal incentive coefficient β^t can be calculated by solving the optimization problem defined by Equation (50).

$$\beta^t = \frac{\beta^o k_{en} k_{ec}}{k_{ec}^2 + \rho\sigma^2 b^t} \quad . \qquad (50)$$

In Step 2, the government knows the strategy of owners and tenants under a certain government incentive. The problem of the government is how to choose the most efficient incentive to induce the efforts of tenants and tenants for green retrofit and optimize the utility of the government. The mathematical expression of this problem is shown in Equation (51).

$$\max_{\beta^0} E(U^g) = \max_{\beta^0}(-\alpha^o + k_{en}(1-\beta^o)(a^o + a^t)) \tag{51}$$

s.t.

(IR): $E(U^t) \geq \omega_0^t$, $E(U^o) \geq \omega_0^o$

(IC): $a^o = \dfrac{\beta^o k_{en}}{b^o}$

$$a^t = \frac{k_{ec} + k_{ec}\beta^t}{b^t}$$

$$\beta^t = \frac{\beta^o k_{en} k_{ec}}{k_{ec}^2 + \rho\sigma^2 b^t}.$$

The optimal incentive coefficient β^o can be calculated by solving the optimization problem defined by Equation (x) (see Appendix II).

$$\beta^o = \frac{1}{2}[1 - \frac{1}{(\frac{k_{en}b^t}{k_{ec}b^o} + (\frac{k_{en}k_{ec}}{k_{ec}^2 + \rho\sigma^2 b^t}))}] \ . \tag{52}$$

6.3.3 Discussion

The optimal incentives and efforts for the four quadrants deduced in the last section are summarized in Table 6.9. These results are for the assumption that tenants are risk averse. If tenants are risk neutral, namely, $\rho = 0$, the results in Table 6.9 can be simplified, as shown in T able 6.10.

Table 6.9 Optimal incentives and efforts for the four quadrants (risk averse)

	II	III	I	IV
β^o	$\beta^o = \frac{k_{en}{}^2}{b^o \rho\sigma^2 + k_{en}{}^2}$	$\beta^o = \frac{k_{en}{}^2}{b^o \rho\sigma^2 + k_{en}{}^2}$	$\beta^o = \frac{1}{2}[1 - \frac{k_{ec}}{k_{en}}]$	$\beta^o = \frac{1}{2}[1 - \frac{1}{(\frac{k_{en} b^t}{k_{ec} b^o} + (\frac{k_{en} k_{ec}}{k_{ec}^2 + \rho\sigma^2 b^t}))}]$
β^t	NA	NA	$\beta^t = \frac{k_{ec}^2 + \beta^o k_{en} k_{ec}}{k_{ec}^2 + \rho\sigma^2 b^t}$	$\beta^t = \frac{\beta^o k_{en} k_{ec}}{k_{ec}^2 + \rho\sigma^2 b^t}$
a^o	$a^o = \frac{k_{ec} + \beta^o k_{en}}{b^o}$	$a^o = \frac{\beta^o k_{en}}{b^o}$	$a^o = \frac{k_{ec} + \beta^o k_{en}}{b^o} = \frac{1}{2} \frac{(k_{en} + k_{ec})}{b^o}$	$a^o = \frac{\beta^o k_{en}}{b^o}$
a^t	NA	NA	$a^t = \frac{\beta^t k_{ec}}{b^t} = \frac{k_{ec}}{b^t} \square \frac{k_{ec}^2 + \beta^o k_{en} k_{ec}}{k_{ec}^2 + \rho\sigma^2 b^t}$	$a^t = \frac{k_{ec} + k_{ec}\beta^t}{b^t}$

Table 6.10 Optimal incentives and efforts for the four quadrants (risk neutral)

	II	III	I	IV
β^o	$\beta^o = 1$	$\beta^o = 1$	$\beta^o = \frac{1}{2}[1 - \frac{k_{ec}}{k_{en}}]$	$\beta^o = \frac{1}{2}[1 - \frac{k_{ec} b^o}{k_{en} b^t + k_{en} b^o}]$
β^t	NA	NA	$\beta^t = 1 + \frac{k_{en}}{k_{ec}} \beta^o = \frac{1}{2}[1 + \frac{k_{en}}{k_{ec}}]$	$\beta^t = \frac{1}{2}[\frac{k_{en}}{k_{ec}} - \frac{b^o}{b^t + b^o}]$
a^o	$a^o = \frac{k_{ec}^o + \beta^o k_{en}^o}{b^o}$	$a^o = \frac{\beta^o k_{en}^o}{b^o}$	$a^o = \frac{k_{ec} + \beta^o k_{en}}{b^o} = \frac{1}{2} \frac{(k_{en} + k_{ec})}{b^o}$	$a^o = \frac{1}{2}(\frac{k_{en}}{b^o} - \frac{k_{ec}}{b^t + b^o})$
a^t	NA	NA	$a^t = \frac{\beta^t k_{ec}}{b^t} = \frac{1}{2} \frac{[k_{en} + k_{ec}]}{b^t}$	$a^t = \frac{k_{ec}}{b^t}(1 + \frac{k_{en}}{2k_{ec}} - \frac{b^o}{2(b^t + b^o)})$

Quadrant II versus Quadrant III

The results show β^o has the same value in Quadrants II and III in Table 6.9, indicating that whether or not owners can get benefits from green retrofit, the government incentives are the same.

Under the same incentive coefficient β^o, $a^o_{\mathrm{II}} \geq a^o_{\mathrm{III}}$, which means owners will have more efforts when they can get economic incomes; the difference between the a^o of the two quadrants is $\frac{k_{ec}}{b^o}$. a^o is positively correlated with k_{ec}, β^o, and k_{en}. This correlation means that the higher the economic benefit coefficient, environmental benefit coefficient, and government incentives, the higher the efforts owners will make. It also indicates that technology development can induce more owner efforts because k_{ec} and k_{en} are higher. Accordingly, a^o is negatively correlated with b^o. This correlation means that the higher the cost coefficient of green retrofit, the lower the efforts owners make. Given that high costs improve the difficulty of green retrofit, it will cause the reluctant attitude of owners.

Quadrant I versus Quadrant IV

Under the same incentive coefficient β^o, $a^o_{\mathrm{I}} \geq a^o_{\mathrm{IV}}$, which means owners will have more efforts when they can get the economic incomes; the difference between the a^o of the two quadrants is $\frac{k_{ec}}{b^o}$.

Under the same incentive coefficient, $a^t_{\mathrm{I}} \leq a^t_{\mathrm{IV}}$, which means tenants will have more efforts when they can get the economic incomes; the difference between the a^t of the two quadrants is $\frac{\rho\sigma^2 k_{ec}}{k_{ec}^2+\rho\sigma^2 b^t}$. When tenants are risk neutral, the difference is zero, $a_{\mathrm{I}}^t = a_{\mathrm{IV}}^t$; otherwise, if $k_{ec} \to \infty$, the difference approaches zero.

Furthermore, $\beta_{\mathrm{I}}^t \geq \beta_{\mathrm{IV}}^t$, which means owners have to give more incentives when tenants cannot get the economic incomes from green retrofit; the difference between the β^t of the two quadrants is $\frac{k_{ec}^2}{k_{ec}^2+\rho\sigma^2 b^t}$.

For the government, the relation between β_{I}^o and β_{IV}^o is uncertain, such that β_{I}^o may be higher, lower than, or the same as β_{IV}^o. The relation between β_{I}^o and β_{IV}^o depends on the relation among b^t, b^o, ρ, σ, k_{ec}, and k_{en}. This relation reveals that when buildings have tenants, the optimal incentives of the government is in high uncertainty and difficult to decide due to the complex relationship and uncertainty between owners and tenants. However, in reality, most commercial buildings are occupied by tenants. This is why policies for green retrofit are difficult to launch and have not achieved satisfactory effects. Therefore, analyzing the relation between owners and tenants is essential for policy making for green retrofit.

Government incentive β^o

In Quadrants II and III, β^o is the same and is negatively correlated with b^o, ρ, and σ. This correlation means the higher the cost coefficient of green retrofit, degree of risk aversion, and uncertainty, the lower the incentives government should provide. As β^o is a factor representing the risk share between government and owner, it indicates that if the cost coefficient of green retrofit, degree of risk aversion, and uncertainty is high, then owners will want to undertake few risks. β^o is negatively correlated with k_{en}. This correlation means that the higher the environmental benefit coefficient of green retrofit, the lower the incentives government should provide. A higher k_{en} means the government can easily get environmental benefits from green retrofit, and so it does not need to provide high compensation.

In Quadrant I, β^o is not correlated with ρ, which means the government incentive is not related to the risk attitude. Regardless of whether the tenant is risk averse or risk neutral, the incentives are the same. β^o only relates to $\frac{k_{ec}}{k_{en}}$. Assuming that $\beta^o > 0$, then there are only incentives but no punishment. Hence, $\frac{k_{ec}}{k_{en}} < 1$, which indicates that only when the environmental benefit of green retrofit k_{en} is higher than economic benefit k_{ec} will it be rational for the government to give incentives.

β^o is much more complex in Quadrant IV than in the other three. The value of β^o depends on the value of b^t, b^o, ρ, σ, k_{ec}, and k_{en}. In reality, most commercial buildings are in Quadrant IV, which is tenant-occupied and owner-unbenefited. Therefore, policies for green retrofit are difficult to make and have not achieved satisfactory effects.

Efforts of owners and tenants

Under the same incentive coefficient β^o, $a^o_{\mathrm{II}} \geq a^o_{\mathrm{III}}$, which means owners will have more efforts when they can get the economic incomes. Under the same incentive coefficient β^o, $a^o_{\mathrm{I}} = a^o_{\mathrm{II}}$, which means no matter if buildings are owner-occupied or tenant-occupied, owners will pay the same efforts when they can get the economic incomes from green retrofit.

a^t is positively correlated with k_{ec} and β^t. This correlation means the higher the economic benefit coefficient and owner incentives, the higher the efforts tenants will make. Given that β^t is positively correlated with k_{en}, a^t is also positively correlated with k_{en}. This correlation indicates that technology development can induce more owner efforts because k_{ec} and k_{en} are higher. Accordingly, a^t is negatively correlated with b^t. Additionally, because of its positive correlation with β^t, a^t is also negatively correlated with b^t, b^o, ρ, and σ. This correlation means the higher the cost coefficient of owners and tenants, the risk averse, and the uncertainty, the lower the efforts tenants make. Given that high costs and uncertainty improve the difficulty of green retrofit, it will cause the reluctant attitude of tenants.

Risk neural $\rho = 0$

If all stakeholders are risk neutral, namely, $\rho = 0$, then $\beta^o_{\mathrm{II}} = \beta^o_{\mathrm{III}} = 1$. This condition indicates that owners will face more risks and get more benefits from green retrofit compared to a risk-averse condition. β^o is not related to k_{ec}, k_{en}, and σ, but it is a constant, which means the government incentives are not related to the external environment.

a^o in Quadrants I, II, and III is the same under different risk preferences because it is not correlated with ρ. This non-correlation indicates that the risk preference does not affect owners' efforts. β^o in Quadrant I is the same under different risk preferences because it is not correlated with ρ. This non-correlation indicates that the risk preference does not affect government incentives. β^t and a^t are higher when risk neutral than when risk averse, which means the incentive to tenants and the efforts of tenants increase when risk decreases.

The results show that $\frac{a^o}{a^t} = \frac{b^t}{b^o}$, which means the proportion of owners' efforts and tenants' efforts are inversely proportional to their cost of green retrofit. If the owners' cost is higher than the tenants', then tenants will give more efforts, and vice versa. Substitutability exists between owners' efforts and tenants' efforts on the basis of their costs of green retrofit.

6.4 Summary of the Chapter

This chapter first analyzed decision making on green retrofit based on a game model between owners and tenants, who are the key decision makers on whether to retrofit during the initial phase. Occupancy types were classified into three categories, namely, owner-occupied, single-occupied (not by owner), and multi-occupied. After comparing the costs and benefits of owners and tenants, the payoff function was proposed under the owner-occupied condition, and payoff matrixes were proposed under single- and multi-occupied conditions. Green retrofit decisions in owner-occupied buildings are relatively easy to make, whereas implementing green retrofit under the other two conditions is difficult, because the Nash equilibrium for owners and tenants is "reluctant to retrofit" and "reluctant to retrofit" respectively.

Government has to be involved to encourage owners to undertake green retrofit through economic incentives, including compensation, tax reduction, and other policies. Besides the owner and tenant, the government was added in the model as a player. According to different occupancy types and utility fee-paying types, green retrofit can be divided into four quadrants. The results showed that the optimal policies are different in each quadrant. This finding means the government should make different policies for different types of buildings, so that the total efficiency of green retrofit can be optimized.

Chapter 7 Agent-based Platform for Decision Making on Green Retrofit

7.1 Introduction

This chapter develops an agent-based platform based on the game theory-based model in the last chapter to facilitate decision making in real green retrofit projects. The platform has two levels: one is for the building level, the other one is for the city level. The building level is used for deciding whether or not a certain building will be retrofitted and the optimal incentive policy, and the end users are mainly the owner of the building, the government, and the third-party institute. The city level is used for a whole city to decide when to retrofit each building and the optimal incentive policy for each building. This chapter is arranged as follows.

Section 7.2 illustrates the framework of the agent-based platform. Section 7.3 introduces the definitions of the agents used in the platform, including their characteristics, parameters, and interrelations. Section 7.4 illustrates the UI and introduces how to use the functions. A friendly interface is essential because the platform is designed for use in the government and the industry. Section 7.5 validates the platform with the existing policies of green retrofit in Shenzhen and Shanghai. The consistency between experiment results and theoretical results can verify the reliability of the platform. Finally, Section 7.6 gives a summary of this chapter.

7.2 Process of platform development

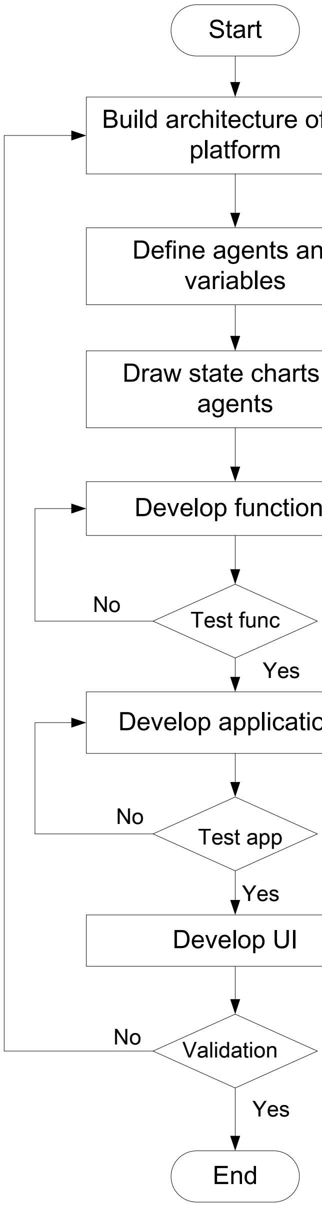


Figure 7.1 Architecture of the agent-based platform

The process of platform development is shown in Figure 7.1. First, the architecture of platform is built. Layered architecture is selected for the agent-based platform. Details of the architecture are introduced in Section 7.3.1. Second, agents and their interactions and variables in the platform are defined. There are four types of agents and several types of variables. The details of agent definition are illustrated in Section 7.4.1. Third, the state charts of agents are drawn to define the states and transition among states. The state charts of agents are introduced in Section 7.4.2. Fourth, the functions in the platform are developed and tested. If the test is passed, UI will be developed in the following step. If not, the functions will be redesigned. Fifth, the UI is developed for the platform. Details of UI design are introduced in Section 7.5. Finally, the whole platform is validated. If the validation results are satisfied, the platform development will be ended. Otherwise, the platform will be modified and redesigned following the same process.

7.3 Framework of the Platform

7.3.1 Architecture of the platform

The architecture of the proposed agent-based platform is shown in Figure 7.2.

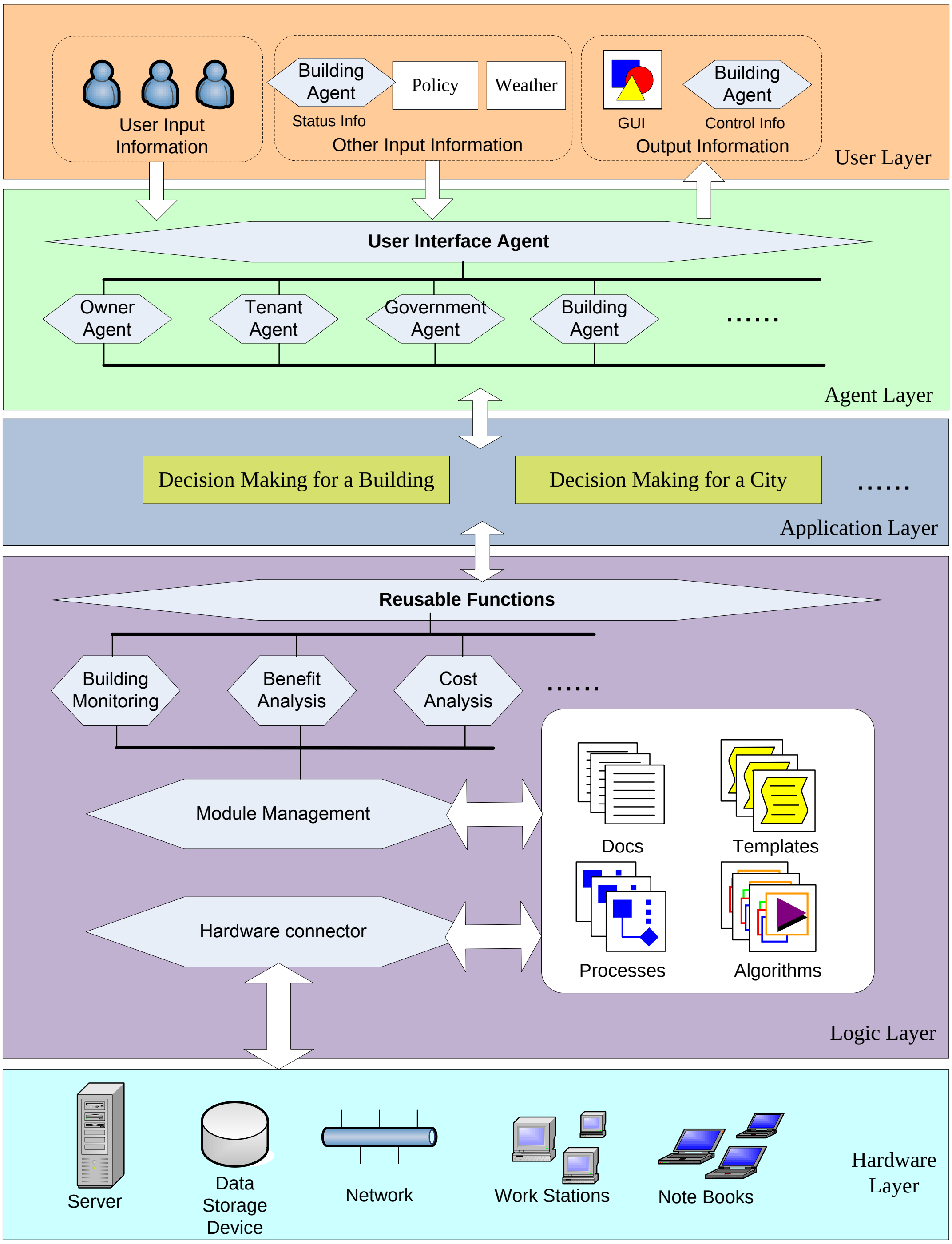


Figure 7.2 Architecture of the agent-based platform

The agent-based platform is implemented in Anylogic 7.2. AnyLogic is a widely used simulation tool of agent-based modelling. The development language of Anylogic is Java. Due to the high compatibility of Java, the developed platform can be adopted in any device supporting Java toolkit, including PC, MAC, mobile phone and etc.

AnyLogic have been widely used in modeling for diverse areas such as manufacturing and logistics, business processes, human resources, consumer and human behavior.

The platform has five layers, namely, user layer, agent layer, application layer, logic layer, and hardware layer. This architecture is developed based on the Open Systems Interconnection (OSI) model , which is a general conceptual model that characterizes and standardizes the communication functions of a telecommunication or computing system without regard to their underlying internal structure and technology, defined in standard ISO/IEC 7498-1. The model partitions a computer system into abstraction layers. The original version of the model defined seven layers, which are application, presentation, session, transport, network, data link and physical layer. A layer serves the layer above it and is served by the layer below it. Two instances at the same layer are visualized as connected by a horizontal connection in that layer. This kind of architecture is modularized and loosely coupling, which provides the system strong flexibility and extendibility. For example, if some new applications or functions are added in the platform, only a few modules and interfaces need to be supplemented or adjusted. Therefore, the agent-based platform is developed based on this layered architecture. The layers are introduced below.

User Layer is mainly for the UI. Users can give input to the system and get output from the system. Besides the manual inputs by users, some other inputs from a database can also be used in the platform, for example, building data, climate data, economic data, and policy data. The outputs of the platform are mainly shown in the graphic UI, which gives users a clear suggestion for decision making on green retrofit and the optimal policy. Furthermore, the output can connect to the building information system and give instructions for implementing green retrofit and its operation after the project.

Agent Layer is mainly for agent definition. This study only has four agents, which are owner agent, tenant agent, government agent, and building agent. As this study focuses on the decision making in the initial phase, not many stakeholders are involved. Depending on the various problems and requirements, some agents can be added to or deleted from the system. For example, the designer agent can be added if the problem being discussed is in the design phase. This layer defines the characteristics, parameters, variables, and relations of agents. These definitions can be used in the application layer and logic layer.

Application Layer is mainly for applications in the platform. In this study, there are two levels of applications, building level and city level. The former is to decide whether to retrofit a certain building and the optimal incentive policy for this building. The latter is to decide whether to retrofit each building in a city and the optimal incentive policy for each building. Besides the suggestions for decision making and incentive policy, these applications can monitor the condition of buildings, GHG emission, energy consumption, and green retrofit progress. In these applications, different strategies, namely, the optimization objectives, can be selected and the results under different strategies can be compared.

Logic Layer is for the logic implementation of the system. In this study, the reusable functions mainly include benefit analysis, cost analysis, building condition monitoring, and energy consumption calculating. These functions can be reused in different applications (e.g., decision making for building, decision making for city) and different strategies (e.g., maximizing the benefit of government, maximizing the effect of green retrofit, and maximizing the total benefit of society); the algorithms and processes can also be reused in different functions. Therefore, the system is efficient and reliable.

Hardware Layer is the fundamental support for the whole system. It includes the data storage devices, workstations, network, and servers (for the website version). The data storage devices are for data storage and data interaction. In Anylogic 7.2, the database is integrated in the software, which uses the hard disks in workstations. The platform runs on a workstation with a Windows 7 64-bit operation system, Intel Core i7-3770 CPU, 8GB RAM and 1TB hard disk. The platform can also run on a website based on a browser–server structure. With a free Java toolkit, other workstations and terminals can access the website and use the platform remotely.

7.3.2 Applications

The agent-based platform has two application levels for green retrofit decision-making support, namely, building level and city level, as shown in Figure 7.3. The details of these two applications are introduced below.

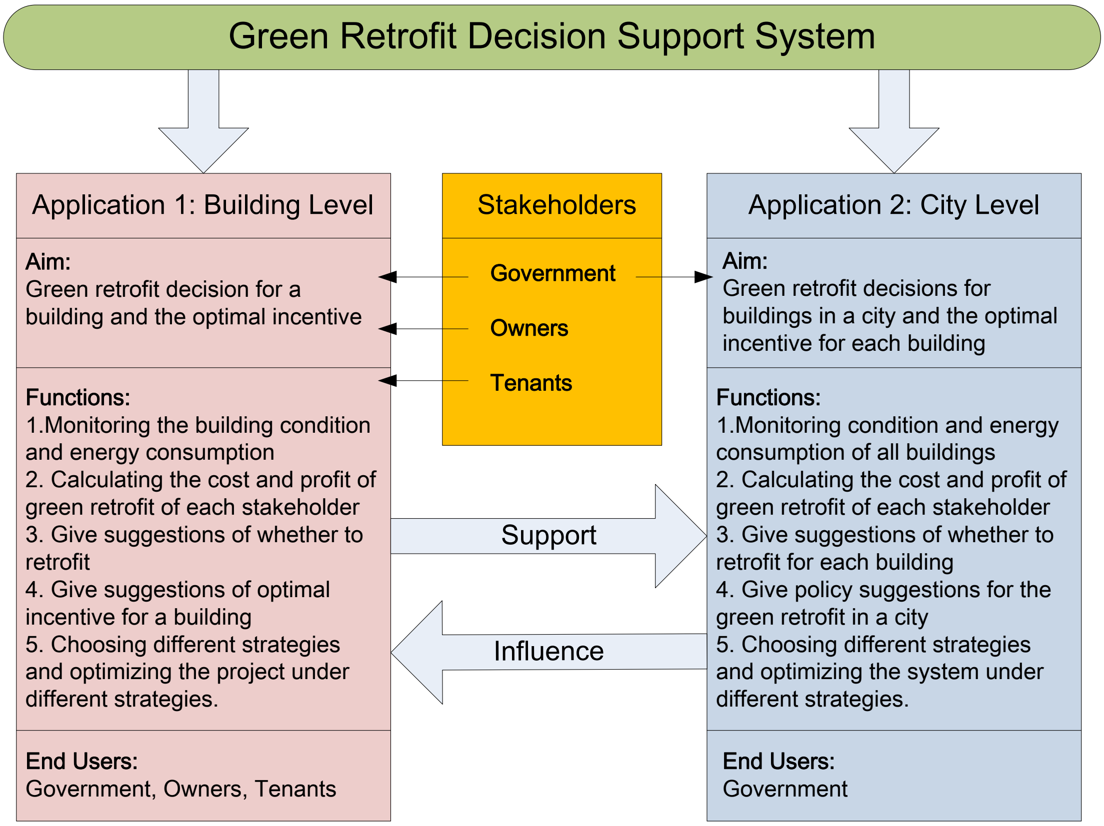


Figure 7.3 Applications of the agent-based platform

Application at building level

The application at building level is designed to support the green retrofit decision of a building and optimize government incentives for the building. The end users of this application are government, owners, and tenants of a specific building. The functions of this application include monitoring the building condition and energy consumption during operation phase, providing suggestions of whether to retrofit, providing suggestions of optimal government incentives, and comparing the conditions under different strategies.

Monitoring the building condition and energy consumption. During the operation phase, the proposed platform can monitor the building condition, energy consumption, energy bills, and GHG emission. It can help the owners and tenants of the building understand the information of the building, especially the energy-related information.

Evaluating the cost and benefit of green retrofit when trigger events happen. If trigger events occur (e.g., the building condition getting worse than a threshold, a new policy launched, a new technology improvement, and a retrofit proposal by owners or tenants), the system will evaluate the cost and benefit of green retrofit according to the situation at that time, including the environmental condition, energy consumption, energy price, energy saving after retrofit, retrofit costs, and so forth. The evaluation results serve as a strong reference for owners and tenants who are making a decision on green retrofit.

Providing suggestions of whether to retrofit. Based on the evaluation results of cost and benefit, the system can provide suggestions to owners and tenants on whether the building should be retrofitted. If the benefit is more than the cost for both owners and tenants, they will be suggested to undertake green retrofit; otherwise, green retrofit is not suggested.

Providing suggestions of the optimal government incentive. If the government wants to promote green retrofit but its benefits cannot attract owners to undertake it, the government should give incentives to owners to encourage them to have green retrofit. The problem is determining how much incentive is the most efficient. The proposed system can give suggestions to the government regarding the optimal incentive value.

Comparing the government incentives and the efforts of owners under different strategies. The government can have different strategies for promoting green retrofit. In this study, three strategies are selected for comparison, including maximizing government profit, maximizing society profit, and fix energy saving rate. The first strategy is to maximize the government profit, which is defined as the environmental benefit minus the government expense (the incentive to owners). The second strategy is to maximize the total profit of the government, owners, and tenants, which is defined as the environmental benefit plus the economic benefit of owners and tenants minus the government expense and costs of owners and tenants. The difference between the first and second strategies is whether the government considers its own profits or the total profits of the society. The last strategy is to achieve the fix energy saving rate. For example, the "20-20-20" plan of the European Union aims to reduce 20% GHG emission before 2020 compared to 1990. Many governments over the world have a specific aim of energy reduction. Thus, it is rational for governments to launch incentive policies to achieve this aim. Suggestions can be provided and compared under these three strategies.

Application at city level

The application at city level is designed to support the green retrofit decision on all public buildings in a city and optimize the government incentives for each building. The functions of this application are similar to the application at building level, but for all public buildings in a city. The end user of this application is only the government.

Monitoring the condition and energy consumption of all buildings. During the operation phase, the proposed platform can monitor the condition of all public buildings in a city, including energy consumption, energy bills, and GHG emission of each building. All the buildings can be illustrated in a map, which shows the location of all buildings and make them easier to find. The monitoring information can help the government understand the information of the buildings in a city.

Evaluating the cost and benefit of green retrofit when trigger events happen. This function is similar to the corresponding function in the application at building level. When trigger events occur for a certain building, the system will evaluate the cost and benefit of green retrofit for that building, and when trigger events occur for all the buildings (e.g., a new policy launched and a new technology improvement), the system will evaluate the cost and benefit of green retrofit for all buildings.

Providing suggestions of whether to retrofit. This function is similar to the corresponding function in the application at building level. However, the difference is that the result of whether or not to retrofit is for the reference of the government. On the basis of the evaluation results of cost and benefit, the system can provide suggestions to government on whether owners will retrofit without government incentives. If yes, the government does not need to offer incentives to the owners of buildings; otherwise, incentives should be provided by the government.

Providing suggestions on the optimal government incentives. This function is similar to the corresponding function in the application at building level. If the government wants to promote green retrofit but the benefit of green retrofit cannot attract owners to do it, the government should give incentives to owners to encourage them to undertake green retrofit. The proposed system can give suggestions to the government regarding the optimal incentive value for each building to ensure that efficiency is maximized.

Comparing the government incentives under different strategies. Similar to the application at building level, three strategies are selected for comparison. The government incentives and the efforts of owners and tenants can be compared under these three strategies.

Relation between the two applications

These two applications are not independent. Although they have different application scenarios and users, technically, they are closely related and work as a whole system. The application of the building level supports the application of the city level as a unit, because the fundamental function of the building level can be reused in the city level. Furthermore, the results of the city level can influence the decision of the building level. For example, the optimal strategies and incentive policies can also change the behaviors of owners and tenants of a building. Therefore, these two applications can work together and provide services to different stakeholders according to their requirements.

7.3.3 Framework

The framework of the proposed platform is shown in Figure 7.4. There are three parts in the framework, namely, process, functions, and data. These parts are shown in different colors in Figure 7.4 (see the legend). The process part illustrates the whole workflow of the system. The function part divides the requirements to functions and provides supports to the workflow. The data part stores the data and has interactions with the system. The framework will be introduced in detail below.

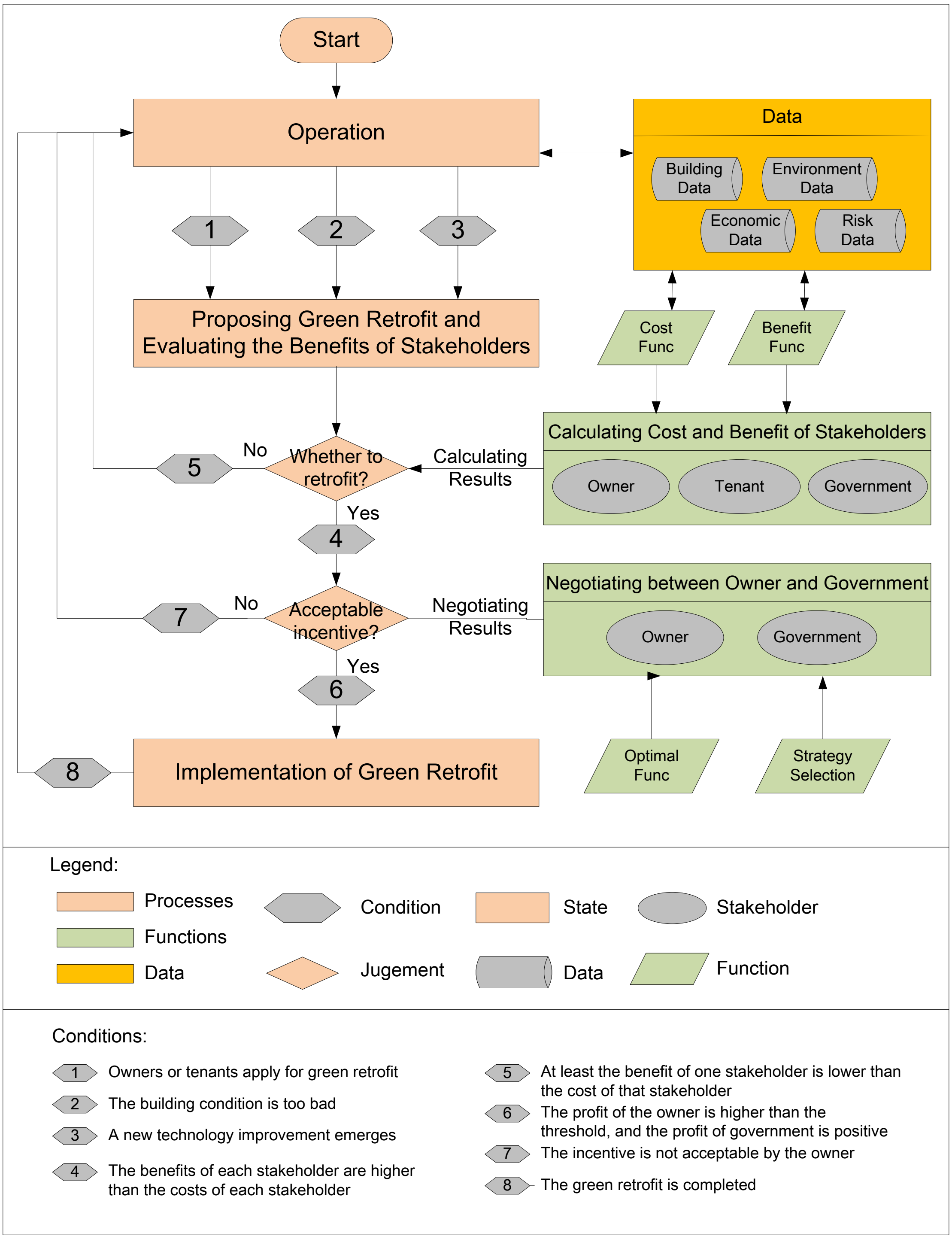


Figure 7.4 Framework of the agent-based platform

At the start point, all the buildings are in the normal operation state. The building information (e.g., energy consumption, building condition, and energy bills), environment information (e.g. environmental condition), economic information (e.g., energy price), and other external information (e.g., risk of green retrofit and technology condition) can interact with the data part, and these types of information can be monitored in real time.

During the operation, if some trigger events happen, the owners of the buildings will consider green retrofit and the system will jump to the state of “proposing green retrofit and evaluating the benefits of stakeholders.” Three trigger events are defined in this study, shown in conditions 1 to 3 in Figure 7.4. The first event is that owners or tenants take the initiative to apply for green retrofit. With the aim of reducing their energy bill or improving the environment, some owners and tenants take the initiative to undertake green retrofit. The second event is that the building condition is too poor. The survey results show that numerous buildings undertake green retrofit during routine renovations. Owners and tenants of a building normally do not want to take the risks of green retrofit because it may affect the systems, structure, and normal operation of the building. However, green retrofit is easier to undertake during routine renovation. The last event is technology improvement. Technology improvement can improve the energy saving of green retrofit, reduce costs, and increase profits. Thus, if a significant technology improvement happens, the stakeholders may reconsider green retrofit.

When the owners of buildings consider green retrofit, the system will help evaluate the effect of green retrofit and calculate the benefits and costs of stakeholders. Some functions are called the function part, including cost function and benefit function. According to the results of these functions, the system can give a suggestion on whether to retrofit. When the benefit of each stakeholder is higher than the cost of each stakeholder (namely, the profit of each stakeholder is positive), then green retrofit is suggested because all stakeholders can benefit from green retrofit.

Otherwise, green retrofit is not suggested because the benefit of at least one stakeholder will be adversely influenced by green retrofit.

If all stakeholders can get benefits from green retrofit, meaning they accept retrofit, the next step will be to judge the optimal incentives. The government and the owner of a building will negotiate with each other. For the owner, there is a threshold, which is called “opportunity cost” in Economics. Besides money, the owner will take time in green retrofit and undertake risks, so he wants to get payback from that. For the government, the aim is to maximize the results of the objective function, which depends on the strategy (i.e., maximizing government profit, maximizing society profit, and fix energy saving rate). The system helps calculate the optimal incentive for the government and check if the owner can accept. If yes, the owner will implement green retrofit based on the committed incentives. If not, the government will increase the incentive slightly and check again if the owner can accept it. These negotiation steps will be iterated until an acceptable incentive is found for both the government and the owner. If no acceptable incentive (the incentive the owner needs is so high that it cannot be accepted by the government) is found, the owner will give up on green retrofit and return to its normal operation state.

If the government and the owner agree on an incentive, the owner will have retrofit and the system will jump into the “implementation of green retrofit” state. After green retrofit is complemented, the system will jump back into the operation state. After green retrofit, some types of data need to be updated, including the energy consumption of the building, energy bills of the building, building condition, environmental condition, and profit of all stakeholders.

7.4 Agent Definition

7.4.1 Agent attributes and interactions

Agents are the core components of the proposed agent-based platform. Agents interact with one another in the simulation environment by processing input information governed by a set of behavior rules to produce different actions. The actions of an agent can also be an input or output by affecting the environment and other agents. To start interacting with other agents and the environment, the agent requires a set of attributes that define its characteristics. There are three kinds of characteristics. The first is static attribute, which refers to some attributes that are static throughout the simulation (e.g., risk preference and degradation rate). The second is time-dependent attribute, which refers to some attributes that change over time depending on the external environmental condition but not the agent action (e.g., building age, energy price, and technology improvement). The third is time- and action-dependent attribute, which refers to some attributes that change over time depending on both external environment and agent actions (e.g., energy consumption of building, building condition, energy saving from green retrofit benefit).

The agent attributes and interactions of the proposed agent-based platform for decision making on green retrofit are shown in Figure 7.5. The large boxes represent the four agent types (building, owner, tenant, and government) and external condition. Agent attributes can be static, time dependent, or both action and time dependent, as shown in the legend in Figure 7.5. Static attributes are represented by rectangles, time-dependent attributes are represented by trapezoids, and attributes that are both static and time dependent are represented by ovals.

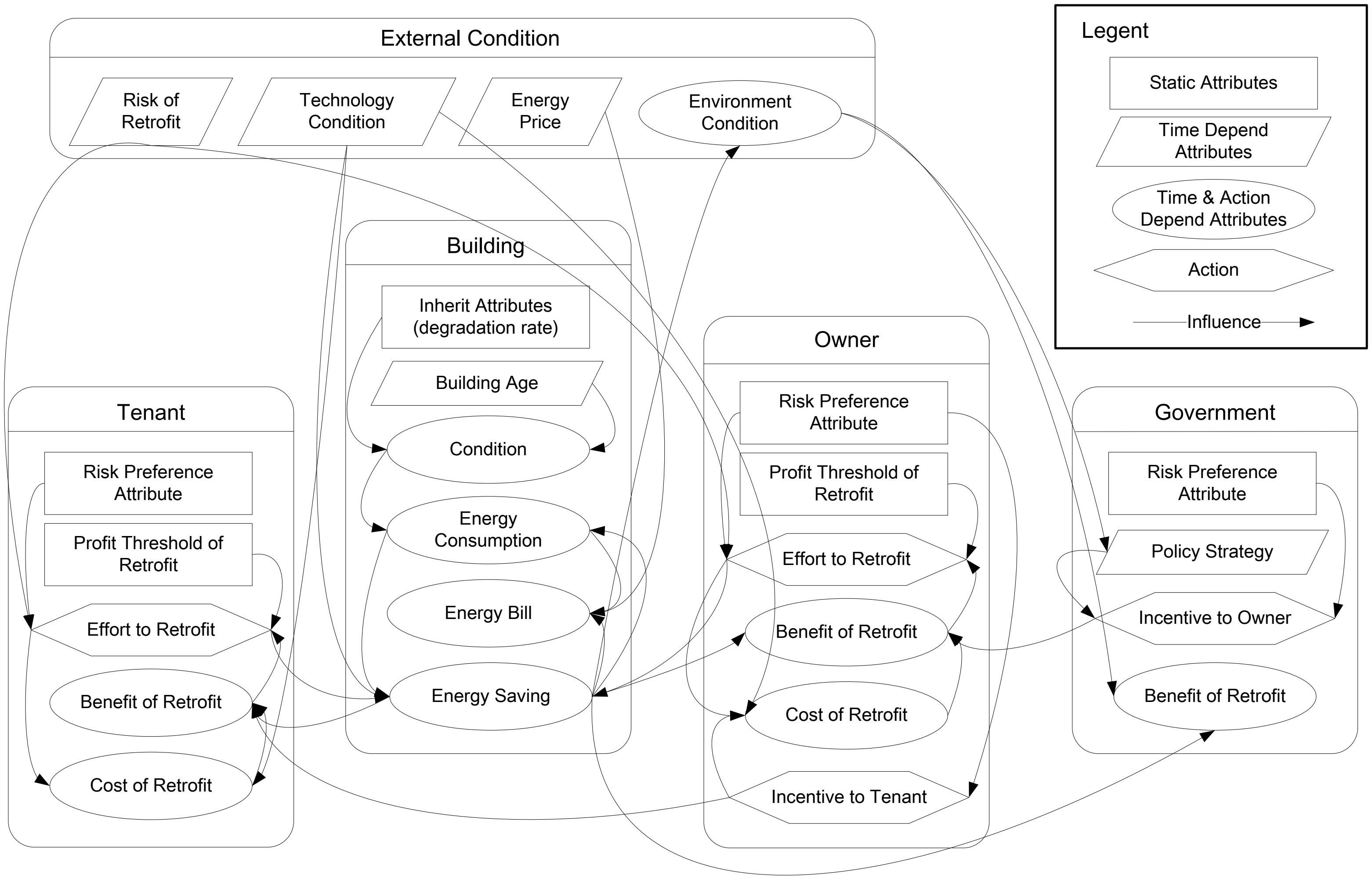


Figure 7.5 Agent attributes and interactions with one another in the simulation environment

Generally speaking, the attributes of an agent can impact other attributes of the said agent and be influences by other attributes. The attributes belonging to different agents can also impact one another through the interactions of agents. The energy saving of green retrofit, efforts of owners, and incentives of government are some of the attributes we are most interested in. The attributes and interactions for each agent are shown in Figure 7.5. Details and examples of how these interactions occur are presented in the following sections.

Owner agent

Owners play a central role in the proposed platform of green retrofit. Owners are responsible for the operation, repair, maintenance, rehabilitation, and renovation of the buildings. They are also the main stakeholder who makes decisions and implement green retrofit. These agents operate their buildings and consider green retrofit when some trigger events happen. Then they evaluate their benefit and cost of green retrofit and negotiate with the government about the incentives. If the profit of green retrofit is high enough, the owners will undertake green retrofit, pay the necessary efforts, and carry the risks. These actions are made to maximize their own profits. Four attributes and two actions are defined for the owner agent.

Risk preference attribute: This attribute determines the risk preference and the preference degree of owners. If the risk preference coefficient ρ=0, owners are risk neutral; if $\rho > 0$, owners are risk appetite; and if $\rho < 0$, owners are risk adverse. The higher the absolute value of ρ, the more extreme the risk appetite or risk adverse. The risk preference attribute is an endogenous variable of owners and will not change over time or be influenced by agent actions. Normally, owners are risk adverse or risk neutral. The value of this attribute will impact the efforts of owners and the incentives to tenants. The more risk adverse the owners, the less efforts they will pay on green retrofit.

Profit threshold of green retrofit: this attribute determines the minimal acceptable profit of green retrofit. Besides the costs of green retrofit, owners have to pay numerous efforts and carry risks, which cause the opportunity cost of owners. Various owners also have various expectations of profits. For example, for some owners of small-scale companies, energy-saving profit is considerable; but for some owners of large-scale companies, energy-saving profit is too small compared to their revenue. Therefore, the profits of green retrofit are needed to cover this opportunity cost and match the expectation of owners. This attribute is an endogenous variable of owners and will not change over time or be affected by agent actions. The value of this attribute will impact the efforts of owners. The higher the threshold value, the lesser the probability owners will have green retrofit.

Benefit of green retrofit: This attribute represents the owners' benefits from green retrofit. It is influenced by other attributes and actions, such as energy saving, incentive from government, and cost of green retrofit. It also influences the efforts of owners. The more benefits from green retrofit, the more efforts owners pay on green retrofit.

Cost of green retrofit: This attribute represents the owners' costs from green retrofit. It is influenced by other attributes and actions, which are the efforts of owner and incentive to tenants. The more efforts owners pay on green retrofit, the more costs they will pay. The costs will impact the benefits of green retrofit. Higher costs will cause fewer benefits.

Efforts to green retrofit: This action indicates the degree of efforts owners pay on green retrofit. The value of this action is from 0 to 1, where 0 means owners do not pay any efforts on green retrofit, and 1 means owners pay 100% efforts on green retrofit. The efforts will influence the cost and energy saving of green retrofit. The more efforts paid by owners, the more cost and energy saving from green retrofit.

Incentive to tenants: This action indicates the incentive coefficient paid by owners to tenants. The incentive from owners to tenants is positively correlated to the economic benefit of green retrofit. The incentive coefficient determines the benefit redistribution between owners and tenants. The higher the incentive coefficient, the more benefits tenants can get from green retrofit. This incentive is a part of the cost of owners and a part of the benefit of tenants.

Building agent

It may be argued that buildings should not be considered true "agents" as they are not autonomous decision makers and do not have learning ability. To this extent, asset can be considered to possess only collaborative behavior, following Nwana's definition (Nwana, 1996). Nonetheless, assets exhibit behavior that is difficult to predict and highly dependent on the interactions with the environment and other agents. The energy consumption of a building changes over time according to many environmental conditions and the retrofit by owner and tenant agents. Therefore, in this study, building is considered a type of agent. The following lists the key attributes of the building agent.

Inherit attribute: This attribute represents the inherit attributes influencing the building operation and retrofit, including degradation rate, building location, and building function. The inherit attribute is an endogenous variable of buildings and will not change over time or be affected by agent actions. The value of this attribute will impact the building condition and difficulty of green retrofit. For example, the building with a higher degradation rate will be in worse condition after the same number of operation years. Moreover, the energy efficiency of buildings in some locations is more difficult to improve due to the climate and other environmental conditions.

Building age: This attribute represents the age of buildings. It is not influenced by other attributes and actions, but only by time. It influences the building condition, in that the more a building ages, the worse its condition.

Building condition: This attribute determines the condition of buildings. The value of this attribute is from 0 to 1, where 0 means the worst condition and 1 means the perfect condition. In this study, if the value of this attribute is higher than 0.7, the building condition is defined as good; if the value is between 0.3 and 0.7, the building condition is fair; and if the value is lower than 0.3, the building condition is defined as poor. The building condition can impact the energy consumption of building. The worse the building condition, the higher the energy consumption because the efficiency of the building systems has deteriorated. This attribute can also influence the initiative of owners and tenants to green retrofit. If the condition is too poor, the trigger event will happen to compel the owners to evaluate the feasibility of green retrofit.

Energy consumption: This attribute represents the energy consumption of a building, which is the main indicator of a building. It is influenced by other attributes and actions, namely, the condition of the building and energy saving by green retrofit. As the base value, the initial energy consumption will influence the energy saving of green retrofit, and after retrofit, it will decrease because of the energy saving. Normally, the energy consumption is compared in the unit of power per square meter (kw/m^2).

Energy bill: This attribute indicates the payment of the energy bill of a building, which is a main cost of building operation. It is influenced by the energy consumption and energy price, and is also a main factor in green retrofit decision. If the energy price is very high and the energy bill per year is very high, then owners and tenants have more initiatives to do green retrofit and save energy. By contrast, if the energy bill of a building is very low, then owners and tenants will not have a strong motivation to retrofit.

Energy saving: This attribute indicates the energy saving by green retrofit, which is the main objective of green retrofit and this platform. This attribute is defined in percentage and the value is from 0 to 1, where 0 means 0% energy and 1 means saved 100% energy by green retrofit. This attribute is influenced by the efforts of owners and tenants, the technology condition, and the building condition. The more efforts paid by the owners and tenants, the more energy savings from green retrofit. Technology improvement can increase energy saving. This attribute influences the economic and environmental benefits of green retrofit and is closely correlated with each stakeholder.

Government agent

The government plays a significant role in the decision making on green retrofit. Government actions influence the economic benefits from green retrofit and, in turn, influence the initiatives of owners and tenants. The government then receives environmental and social benefits from reducing energy consumption and GHG emission. As owners and tenants do not want to have green retrofit without incentive policies, the government has to promote green retrofit by providing incentives and optimizing the objective function. Three attributes and one action are defined for the government agent.

Risk preference attribute: This attribute determines the risk preference and preference degree of owners. If the risk preference coefficient $\rho=0$, government is risk neutral; if $\rho > 0$, government is risk appetite; and if $\rho < 0$, government is risk adverse. The higher the absolute value of ρ, the more extreme the risk appetite or adverse. The risk preference attribute is an endogenous variable of the government, which will not change over time or be affected by agent actions. The government is defined as risk neutral because of its initiative promotion. The value of this attribute will impact the benefit redistribution between the government and owners. If the government is risk neutral and owners are risk adverse, the former has to give additional incentives to compensate for the risk premium of owners.

Policy strategy: As aforementioned, the government has three strategies (i.e., maximizing government profit, maximizing society profit, and fix energy saving rate). These strategies represent the objectives of the government and can be selected manually. As this attribute is in the highest level, it may change over time but will not be affected by other actions.

Incentive to owner: This action indicates the incentive coefficient paid by the government to owners. The incentive from the government to owners is positively correlated to the environmental benefit of green retrofit, which is the main benefit of the government. The incentive coefficient determines the benefit redistribution between the government and tenants. The higher the incentive coefficient, the more benefit owners can get from green retrofit but the lower benefit the government can have. This incentive is a part of the government cost and a part of the benefit of owners.

Benefit of green retrofit: This attribute represents the government benefit from green retrofit. The main benefits for the government are energy saving and, accordingly, improvement of the environment. This attribute is influenced by the energy saving of the building and the improvement of environmental condition. The more the energy saving, the more the benefits government can obtain. In addition, for the same energy saving, the government can have more benefits when the environmental condition is worse, but less benefits when the environment condition is better because marginal efficiency declines. If the environment condition is good enough, the government will not have the initiative to improve green retrofit.

Tenant agent

Tenant is not a compulsory agent in the proposed platform of green retrofit. It only exists in the tenant-occupied building type. In this type of building, tenants are real users, and so the operation, repair, and retrofit of the buildings will impact their direct interests. They are also the main stakeholder in the green retrofit implementation and energy use after retrofit. If tenants do not cooperate with owners in green retrofit or use energy in wasting mode, the effect of energy saving will not be as expected. Therefore, tenants play an important role in green retrofit implementation. To encourage tenants to pay efforts in green retrofit, owners must give them some incentives. If the profit of green retrofit is high enough, then tenants will cooperate in green retrofit, pay efforts accordingly, and carry the risks. These actions are made to maximize their own profits. Four attributes and two actions are defined for the owner agent.

Risk preference attribute: This attribute determines the risk preference and preference degree of tenants. If the risk preference coefficient ρ=0, tenants are risk neutral; if $\rho > 0$, tenants are risk appetite; and if $\rho < 0$, tenants are risk adverse. The higher the absolute value of ρ, the more extreme the risk appetite or risk adverse. The risk preference attribute is an endogenous variable of owners, which will not change over time or be influenced by agent actions. Normally, tenants are risk adverse because most of them will not stay in a building for a long time and do not want to take risks to get long-term payback. The value of this attribute will impact the efforts of tenants. The more risk adverse the tenants, the less efforts they will pay on green retrofit. Therefore, more incentives should be paid to them.

Profit threshold of green retrofit: This attribute determines the minimal acceptable profit of green retrofit. Tenants have to pay numerous efforts and carry risks (e.g., interrupting work, reducing productivity, and high noise during retrofit), which cause opportunity cost for tenants. In addition, various tenants have different expectations of profits. Therefore, the profits of green retrofit are needed to cover this opportunity cost and match the expectation of different tenants. This attribute is an endogenous variable of tenants and will not change over time or be influenced by agent actions. The value of this attribute will impact the efforts of tenants. The higher the threshold value, the lesser the probability tenants will have to green retrofit.

Benefit of green retrofit: This attribute represents the tenants' benefits from green retrofit. It is influenced by other attributes and actions, which are energy saving, incentive from owner, and cost of green retrofit. It influences the efforts of tenants. The more benefits from green retrofit, the more efforts tenants will pay on green retrofit.

Cost of green retrofit: This attribute represents the tenants' costs from green retrofit. It is influenced by other attributes and actions, which are the efforts of tenant. The more efforts owners pay on green retrofit, the more costs they will pay. The costs will impact the benefits of green retrofit. Higher costs will cause fewer benefits.

Efforts to green retrofit: This action indicates the degree of efforts tenants pay on green retrofit. The value of this action is from 0 to 1, where 0 means tenants do not pay any efforts on green retrofit, and 1 means tenants pay 100% efforts on green retrofit. The efforts will influence the cost and energy saving of green retrofit. The more efforts the tenants pay, the more energy savings from green retrofit and higher cost of tenants.

External conditions

Risk of green retrofit: This factor determines the degree of risk of green retrofit. As aforementioned, the exogenesis uncertainty of green retrofit follows the probability distribution, which has a mean of 0 and a variance of σ. The higher the σ, the higher the risk. The risk is exogenous, which means it depends on the climate, environment, technology, and other conditions. It changes overtime but is not influenced by agent actions. The risk of green retrofit can influence the initiative of owners and tenants. If the risk is too high, few owners will take green retrofit.

Technology condition: This factor determines the technology development related to green retrofit. The higher technology condition can improve the efficiency of green retrofit. Specifically, the same efforts and cost of green retrofit can achieve more energy saving. Hence, this attribute can influence the cost and energy saving of green retrofit. Normally, a significant energy improvement happens randomly and cannot be predicted.

Energy Price: This factor determines the energy price. Energy price is an exogenesis variable and changes over time. High energy price can enhance the initiative and efforts of owners to green retrofit.

Environment condition: This factor determines the environment condition. It can influence the strategy of the government and the environmental benefit from green retrofit. When the environment condition is worse, the government will change to a more aggressive strategy to promote the green retrofit, and the same energy saving will bring more benefits to the government. In turn, this factor is also influenced by energy saving. The more energy savings from green retrofit, the better the change for the environment condition.

7.4.2 State chart of agents

The state chart of agents illustrates the state and behavior rules of agents. It includes two key elements, namely, state and transition rule. The former indicates the situation agents are in or the behavior agents are doing, for example, the operation, evaluation, and implementation of green retrofit. The latter indicates how agents switch from one state to another. This transition happens when trigger events occur, some judgment conditions are satisfied, and the time of one state is terminated. On the basis of the states and transition rules, agents have their activities in the state chart autonomously and asynchronously. The state charts of agents are introduced below.

Building agent

The four states of owner agent are operation state, need retrofit, negotiating incentives, and implementing green retrofit, as shown in Figure 7.6.

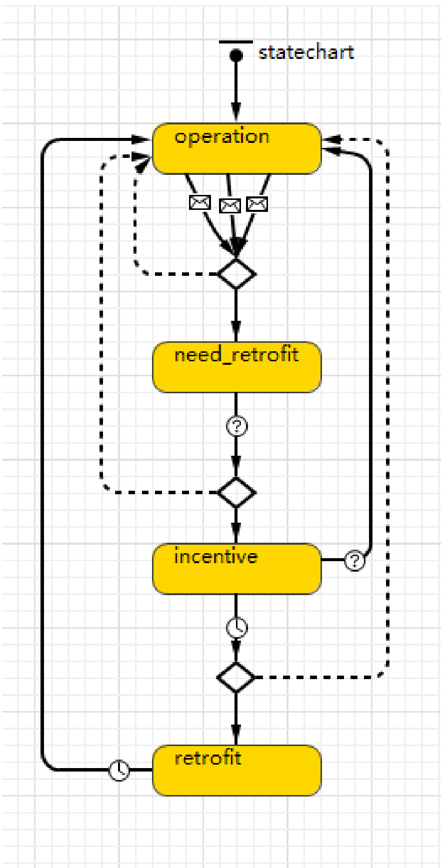


Figure 7.6 State chart of the building agent

Operation state: This state is the normal operation state. At the beginning of the simulation, all buildings are in operation state. If one of the three trigger events happens (i.e., owners or tenants take the initiative to apply for green retrofit, the building condition is too poor, and a significant technology improvement), the building will move out of this state and will be evaluated for the feasibility of green retrofit.

The next state depends on the evaluation result. If the condition of the building is too poor or the profit of green retrofit is high enough, the next state of the building will be "need retrofit"; otherwise, the building will not need retrofit and the next state will return to the "operation state."

Need retrofit state: This state represents the building needing retrofit. However, whether or not to retrofit the building is decided by the owner. If the owner cannot get enough benefit from green retrofit (e.g., the cost or risk of green retrofit is very high), then the retrofit will not be implemented. Therefore, the next state depends on the owner's benefit. If the owner's benefit is high enough, the next state will be "negotiating incentive"; otherwise, the next state will return to the "operation state."

Negotiating incentive state: This state denotes that the incentive of green retrofit is negotiated by the owner and the government. After the owner decides to undertake green retrofit, the next problem is deciding the optimal incentive that can induce the most efficient efforts to green retrofit. This problem is addressed in this state.

The next state depends on the result of the optimal incentive calculation. If no solution of optimal incentive is found, then there is no collaboration between the owner and the government, and the next state will return to the “operation state.” If a solution of incentive exists, but the owner cannot accept it because of high risk adverse and other reasons, then the owner and government will also be unable to collaborate with each other and the next state will return to the “operation state.” If a solution of incentive is found and the owner accepts it, then the owner and government will collaborate and the next state will be “green retrofit.”

Implementing green retrofit: This state is the green retrofit state. The building is being retrofitted when it is in this state. When the green retrofit is completed, the building agent will jump out of this state and return to the “operation state.”

Owner agent

The three states of owner agent are operation state, negotiating incentives, and implementing green retrofit, as shown in Figure 7.7.

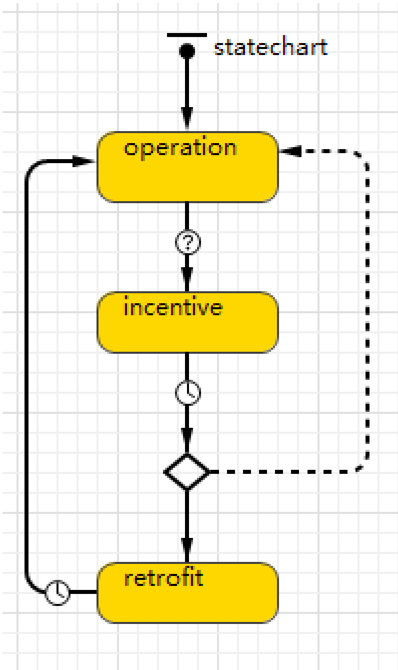


Figure 7.7 State chart of the owner agent

Operation state: This state is the normal operation state, which corresponds to the operation state of the building agent. At the beginning of the simulation, all buildings are in the operation state. If the building is decided to require retrofitting, the owner agent will move to the next state, namely, "negotiating incentives."

Negotiating incentive state: In this state, the owner and the government negotiate the incentive of green retrofit. If they can reach a consensus and collaborate with each other, the owner agent will move to the next state, namely, "implementing green retrofit"; otherwise, the green retrofit will not be implemented and the next state will be "operation."

Implementing green retrofit: This state is the green retrofit state, which corresponds to the implementing green retrofit state of the building agent. The building is being retrofitted when it is in this state. When the green retrofit is completed, the owner agent will jump out of this state and return to the "operation state."

Government agent

The two states of the owner agent are idle state and deciding incentive state, as shown in Figure 7.8.

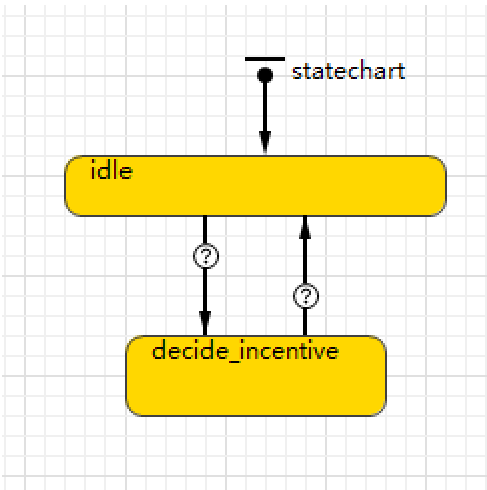


Figure 7.8 State chart of the government agent

Idle state: This state is the normal state of the government when the building is in the operation state. The government is in this state at the beginning of the simulation. If the building is decided to require retrofitting, the owner agent will negotiate the incentive with the government, and the government agent will move into the next state, namely, "deciding incentive."

Deciding incentive: In this state, the owner and the government negotiate the incentive of green retrofit. The government proposes an optimal incentive to maximize the objective function according to the selected strategy. Then the owner agent considers the incentive and decides whether to accept it. If they can reach a consensus and collaborate with each other, the owner agent will implement the green retrofit; otherwise, the green retrofit will not be implemented. Regardless of the result, government agent will return to the idle state.

7.5 User Interface

User interface (UI) is an important part of the decision-making platform in green retrofit. A friendly UI can help users easily obtain information and operate the system. Given that the proposed platform is designed for two levels, building and city levels, the UI is also designed for these two levels. The interface for the two levels is introduced in the following sections.

7.5.1 User interface for the building level

The UI for building level is mainly for building information, operation, assessment of green retrofit, and decision making on green retrofit. This UI has five zones, namely, simulation control, main information, monitor, assessment, and console zones (Figure 7.9).

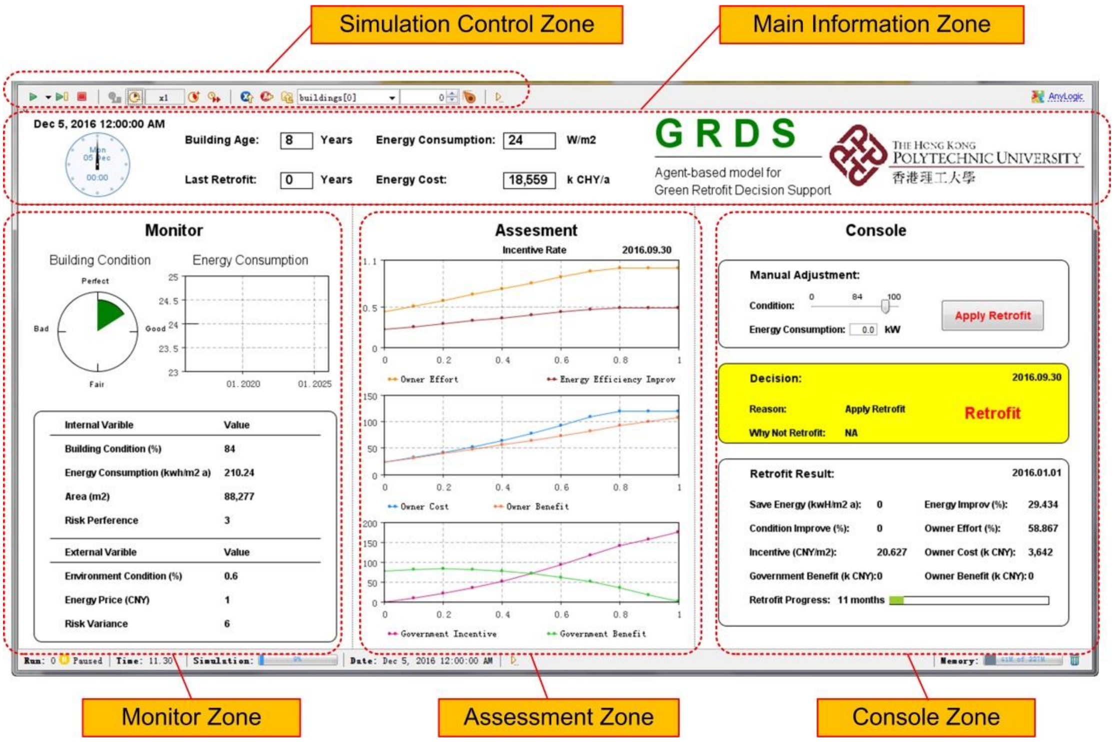


Figure 7.9 User interface for the building level

Simulation zone

Simulation zone is mainly for the functions of simulation, including adjusting simulation speed, pause/stop simulation, selecting view area, navigating to different agents, and so forth.

Main information zone

Main information zone is for exhibiting the main information of the building. The time in simulation is on the top left. The four variables shown in the main information zone are building age, energy consumption, energy bill, and years since the last retrofit. Building age indicates how many years the building has been used. Energy consumption shows the electric power per square meter, which is easy to compare among buildings. Energy bill shows how much the energy bill is per square meter per year. The last variable indicates how long the building has not taken retrofit.

Monitor zone

Monitor zone is for monitoring the factors of the building. When the value of factors becomes abnormal, the system will send a warning and provide a suggestion of green retrofit.

Building condition: The real-time building condition is illustrated in a pie chart shown in Figure 7.10. The condition is represented by the area of the pie chart. A smaller area means a higher quality of the building condition. Three colors are used to indicate the condition and provide direct warnings. When the building is in good condition, the color is green. When the building is in fair condition, the color is orange and stakeholders need to pay attention to the building. When the building is in poor condition, the color will change to red to warn stakeholders that the building needs a retrofit.

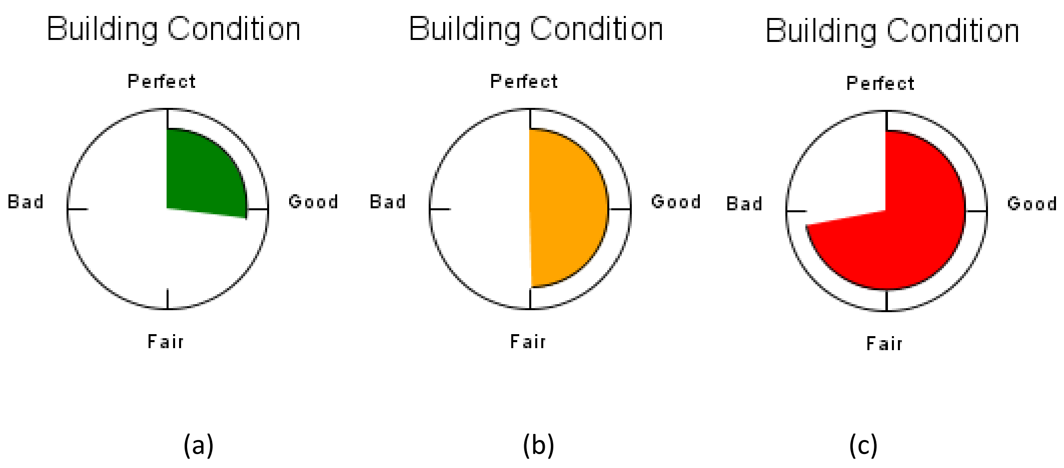


Figure 7.10 Building condition illustrated in UI

(a) Good condition; (b) Fair condition; (c) Bad condition

Energy consumption: The real-time energy consumption is illustrated in a time sequence chart shown in Figure 7.11. The x axis represents the time and the y axis represents the energy consumption (electric power per square meter). This figure shows the trend of energy consumption. For example, the energy saving of a green retrofit can be directly visualized and compared to the past in this figure.

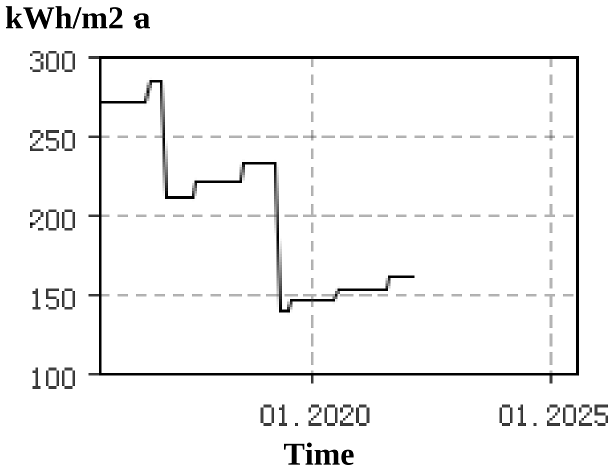


Figure 7.11 Energy consumption of a building illustrated in UI

Variables of building: The real-time variables of a building are shown in the table on the bottom left. There are two parts of the variables, internal and external. The internal variables are related to the building, including building condition, energy consumption, energy bill, and risk preference. The external variables are not directly related to the building, but can influence the result of green retrofit, including environment condition, energy price, and risk variance.

Internal Varible	Value
Building Condition (%)	81.38
Energy Consumption (kwh)	160.806
Energy Bill (CNY)	138.91
Risk Perference	3
External Varible	**Value**
Environment Condition (%)	0.806
Energy Price (CNY)	1
Risk Variance	5

Figure 7.12 Variables of a building illustrated in UI

Assessment zone

Monitor zone is for assessing the factors among stakeholders, including efforts, cost, benefit, incentive, and energy efficiency improvement.

The first figure in the assessment zone (Figure 7.13) illustrates the relation between owner efforts and energy efficiency improvement of green retrofit. The x axis represents the incentive rate, and the y axis represents the percentage. The yellow line represents the owner effort, and the red line represents the energy efficiency improvement. Both owner efforts and energy efficiency improvement should be positively correlated with incentive. Owner effort should also be positively correlated with energy incentive efficiency improvement. The greater the efforts, the more the efficiency will be improved.

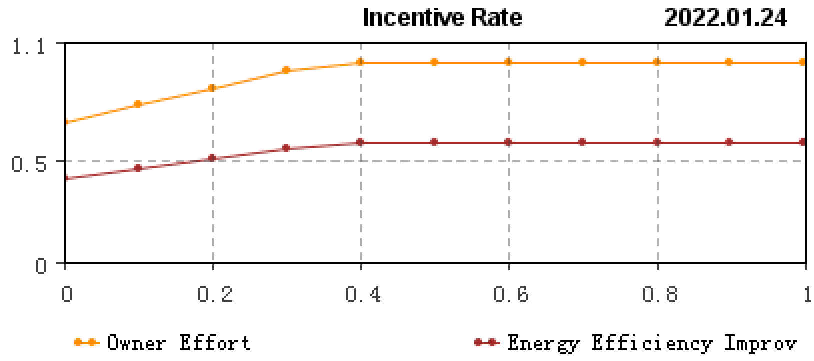


Figure 7.13 Relation between owner effort and energy efficiency improvement

The middle figure in the assessment zone (Figure 7.13) illustrates the relation between cost and benefit of owner if green retrofit is undertaken. The x axis represents the incentive rate, and the y axis represents the percentage. The orange line represents the benefit of owner, and the blue line represents the cost of owner. Both cost and benefit of owner should be positively correlated with incentive. When benefit is higher than cost, the owner can get profit from green retrofit.

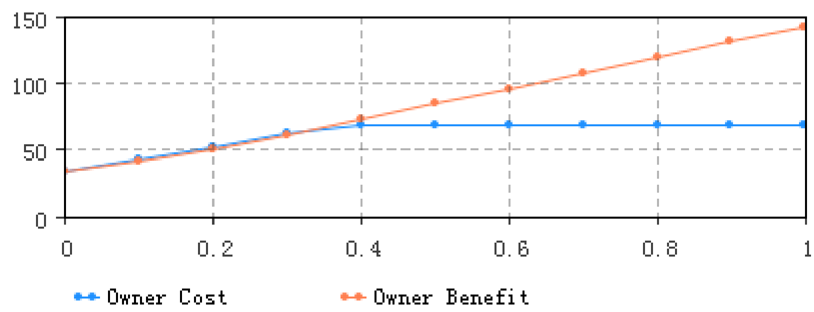


Figure 7.14 Relation between cost and benefit of owner illustrated in UI

The last figure in the assessment zone (Figure 7.15) illustrates the relation between incentive and benefit of government if green retrofit is undertaken. The x axis represents the incentive rate, and the y axis represents the percentage. The purple line represents the incentive of government, and the green line represents the benefit of government. The benefit of government should be negatively correlated with incentive because incentive is a cost of government.

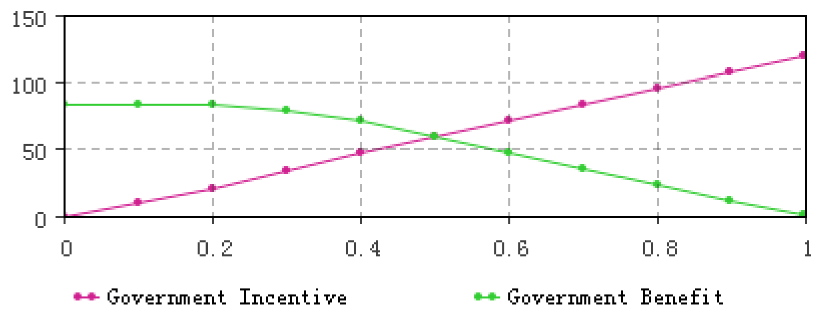


Figure 7.15 Relation between incentive and benefit of government illustrated in the UI

Console zone

Console zone is for observing and controlling green retrofit, including decision making, applying green retrofit, and retrofit results.

Manual adjustment: This window can adjust the building condition and energy consumption, as well as apply green retrofit manually. In some situations, the observed data in the monitor zone may not be accurate and complete. Stakeholders can use this window to input the value of building condition and energy consumption. Furthermore, stakeholders can apply green retrofit manually when they want to propose a green retrofit.

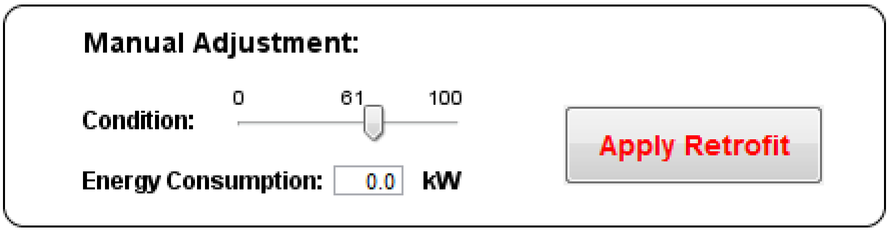
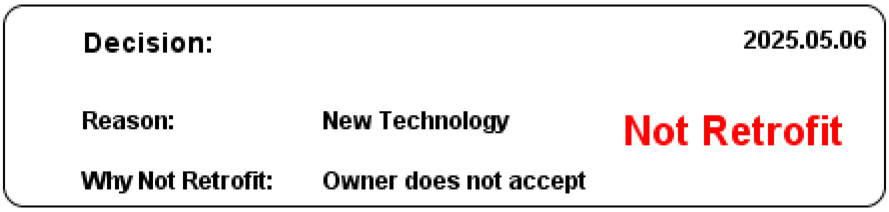
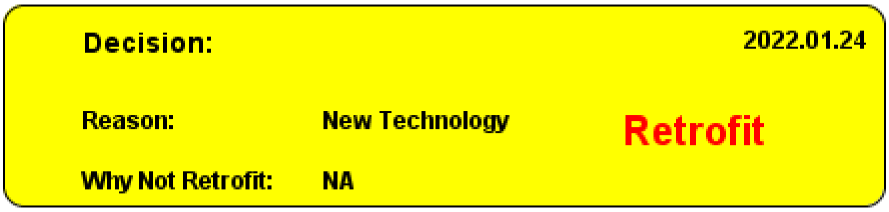


Figure 7.16 Manual adjustment window illustrated in the UI

Decision making on green retrofit: This window (Figure 7.17) shows the decision making on and corresponding reasons of green retrofit. The “reason” in this window illustrates why the building is considered to require retrofit, including new technology, poor condition, and manual application. The decision result is shown on the right in red and bigger font. If the result is “not retrofit,” the reason will be shown in the window, see Figure 7.17 (a). If the result is “retrofit,” the “why not retrofit” reason will be shown as “NA” , see Figure 7.17 (b).



(a)



(b)

Figure 7.17 Results of decision making illustrated in the UI

(a) decision to not retrofit; (b) decision to retrofit

Results of green retrofit: This window (Figure 7.18) shows the results of green retrofit. The results include energy saving, improvement of building condition, improvement of energy efficiency, incentive of government, and benefit of owner and government. The progress of green retrofit is also shown dynamically in the green progress bar.

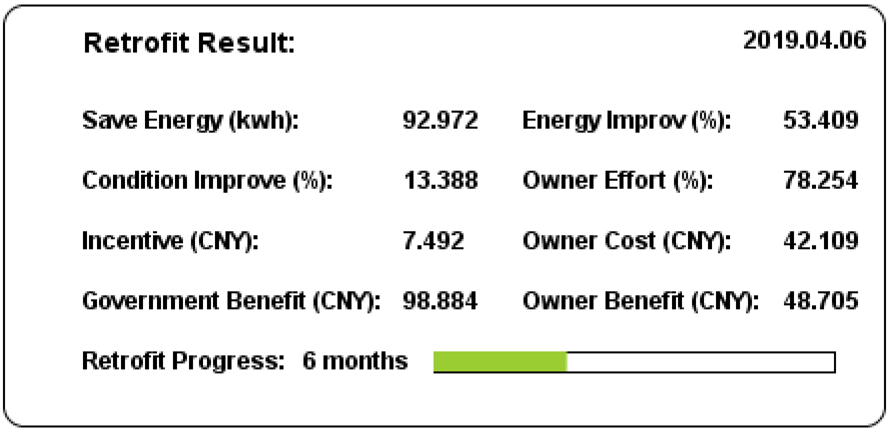


Figure 7.18 Results of green retrofit illustrated in UI

7.5.2 User interface for the city level

The UI for the city level is mainly for the building information, energy consumption information, and green retrofit information of a whole city. The three zones of this UI are main information zone, map exhibition zone, and monitor zone.

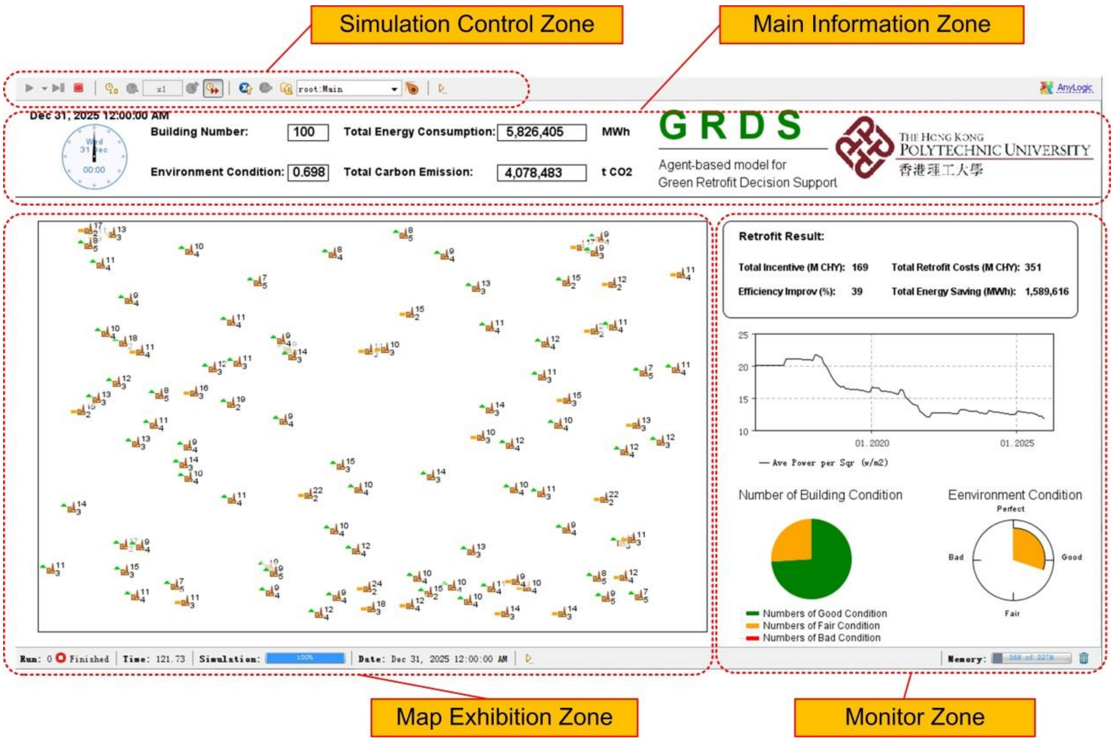


Figure 7.19 User interface for the city level

Main information zone

Main information zone is for exhibiting the key information of buildings. The time of simulation is on the top left. The four variables shown in the main information zone are building number, total energy consumption, environment condition, and total carbon emission. Building number indicates how many buildings exist in the city. Energy consumption shows the total electric consumption of buildings. Environment condition shows the environment index. The total carbon emission illustrates the carbon emission of buildings related to the energy consumption.

Map exhibition zone

The map exhibition zone illustrates the location of buildings on the map and the key information of each building. The color of the building icon illustrates the condition of buildings; green for good, orange for fair, and red for poor. The top number of the building illustrates the electric power per square meter, and the bottom number of the building illustrates the times of green retrofit.

Monitor zone

Monitor zone is for monitoring the factors of the whole city. When the value of the factors becomes abnormal, the system will send a warning.

Retrofit results: The key information of retrofit is illustrated in a table, including the total incentives for green retrofit, total cost, energy efficiency improvement, and total energy saving. The energy efficiency improvement is compared to the average energy efficiency at the starting point.

Average power per square meter: The average power per square meter is illustrated by a figure, which shows the changes in real time. The value is the average power for the whole city, which is a key indicator of the energy efficiency. If the value increases, the government should pay more attention on green retrofit.

Building and environment condition: The building condition is illustrated by a pie chart. Three colors are used to indicate the number of buildings in different conditions; green for when the building is in good condition, orange for fair condition, and red for poor condition. If the areas of orange and red are growing, these colors give the government warning on the building condition in the city. The environment condition is also illustrated by a pie chart. Three colors are used to indicate the number of buildings in different conditions, similar to the color of the building condition. When the environment is in poor condition, the color will change to red to warn the government that policies are needed to improve the environment condition.

7.6 Validation

7.6.1 Background and configuration

A total of 60 million square meters of public buildings are planned to be retrofitted in the "12th Five-Year Plan" of China. To achieve this target, the government selected Shanghai, Shenzhen, Tianjin, and Chongqing as pilot cities in which to experiment on green retrofit policies. Of the four pilot cities, Shanghai and Shenzhen are considered as first-tier cities in China. Therefore, this study selects Shanghai and Shenzhen as examples to simulate the effects of retrofit policies compared with those of the proposed policy.

The policies of Shanghai and Shenzhen for promoting green retrofit are different. For Shanghai, if the improvement of energy efficiency is higher than 20%, the government will give 40 CNY/m^2 subsidy to the owner of the building. If the improvement of energy efficiency is lower than 20%, no subsidy will be given by the government, as shown in Figure 7.20. For Shenzhen, if the improvement of energy efficiency is higher than 20%, the government will give 40 CNY/m^2 subsidy to the owner of the building. If the improvement of energy efficiency is lower than 20% but higher than 10%, the government subsidy will be linear with the improvement rate. If the improvement of energy efficiency is lower than 20%, no subsidy will be given by the government, as shown in Figure 7.21.

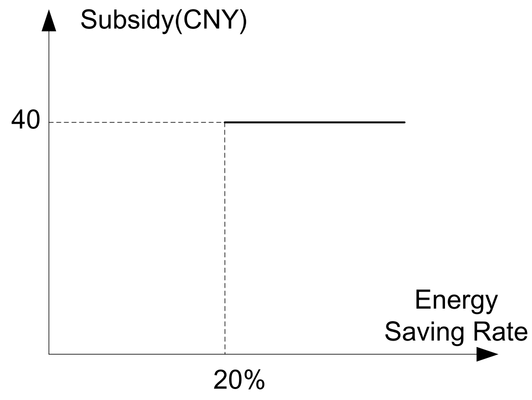


Figure 7.20 Policy of Shanghai for green retrofit

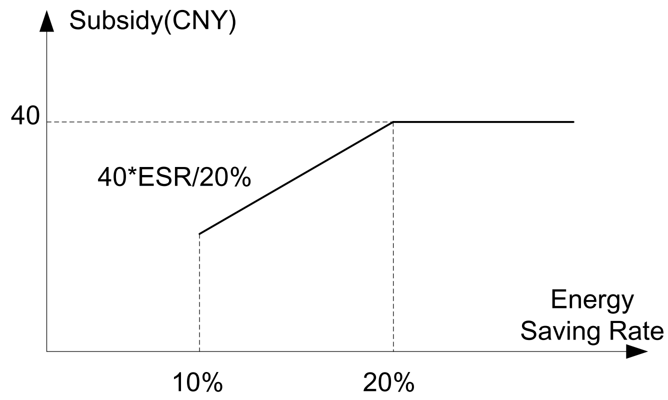


Figure 7.21 Policy of Shenzhen for green retrofit

The simulation of this study includes three scenarios: the proposed game model (introduced in Section 6.3), the policy of Shanghai, and the policy of Shenzhen. The results of these three scenarios will be compared to illustrate the differences of the policies. To simulate the three policy scenarios, the agent-based simulation environment and variables are configured as below. Since the energy consumption data in China is confidential, the data used in validation is hypothetical data. Although the data is hypothetical, since the comparison is based on the same data, it can indicate the performance of the platform.

Table 7.1 Configuration of the simulation experiment

Variable	**Unit**	**Initial Value**	**Definition**
Building number	NA	100	Number of buildings in a city
Age of building	year	0–30	Building age
Area of building	k m^2	2–10	Building area
Variance of uncertainty	NA	6	Risk of green retrofit
Effort of green retrofit	%	NA	Owners' effort paid on green retrofit
Effort coefficient	NA	0.5	Energy improvement rate of max effort
Cost coefficient	CNY	200	Cost of green retrofit effort
Risk coefficient	NA	3	Degree of risk aversion
Environment coefficient	%	0.6	Degree of environment
Energy price	CNY/kWh	1	Electric cost per kWh
Electric power	W/m^2	1	Electric power per square meter
Technology improvement	%	1-20%	Technology improvement rate
Technology breakthrough	Times/year	0.2-0.5	Technology breakthrough times per year
Threshold of owner	%	0	The least acceptable benefit rate of owner

7.6.2 Simulation results

This study applied 10 simulated years, from January 1, 2016 to December 31, 2025. The green retrofit decisions of different scenarios in the simulation process are shown in Figures 7.22 to 7.24. In Figure 7.22, the violet line shows the government incentive, which is zero when the improvement is less than 20%, and 40 CNY/m^2 when the improvement is more than 20%. This finding is consistent with the policy of Shanghai in Figure 7.23. In Figure 7.24, the violet line shows the government incentive, which is zero when the improvement is less than 10%, linear with improvement when the improvement is between 10% and 20%, and 40 CNY/m^2 when the improvement is more than 20%. These results are consistent with the policy of Shenzhen in Figure 7.24.

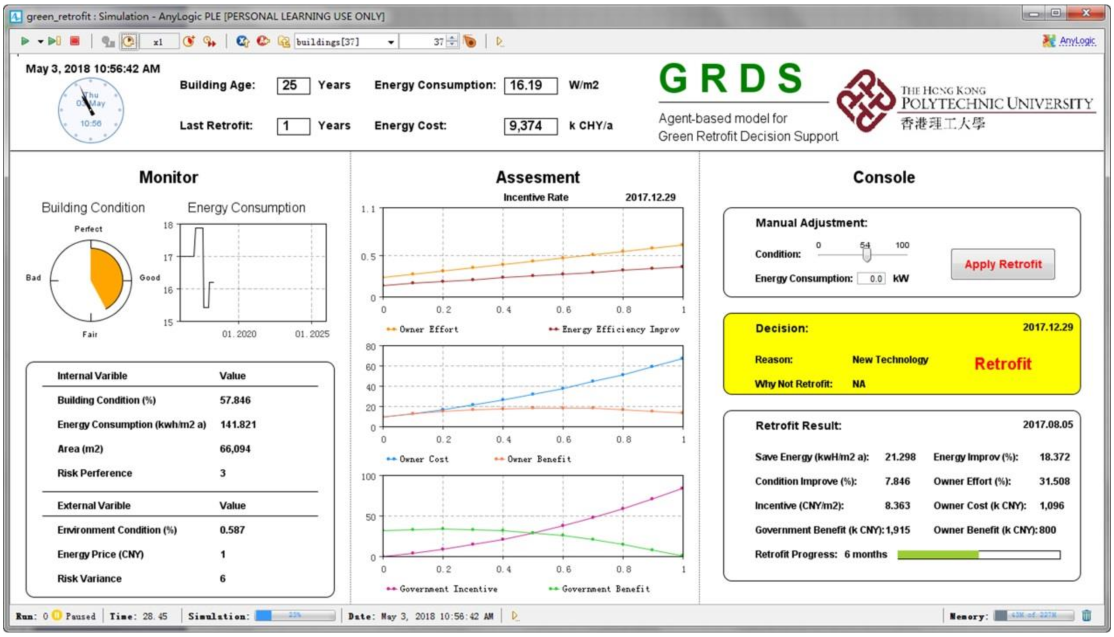


Figure 7.22 Screen capture of scenario 1 (the proposed method)

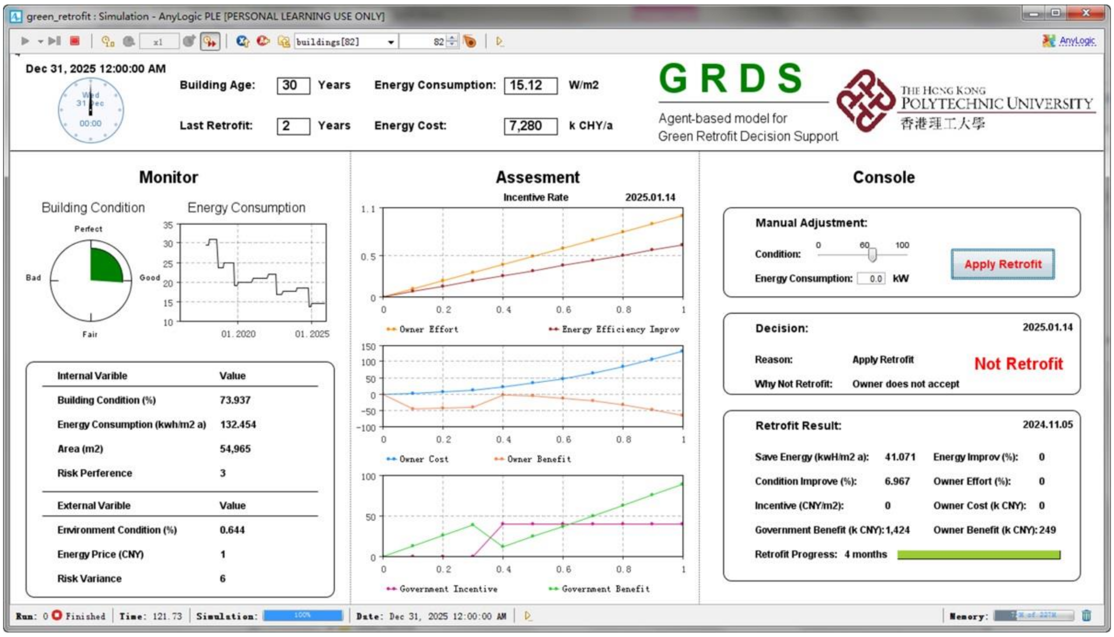


Figure 7.23 Screen capture of scenario 2 (policy of Shanghai)

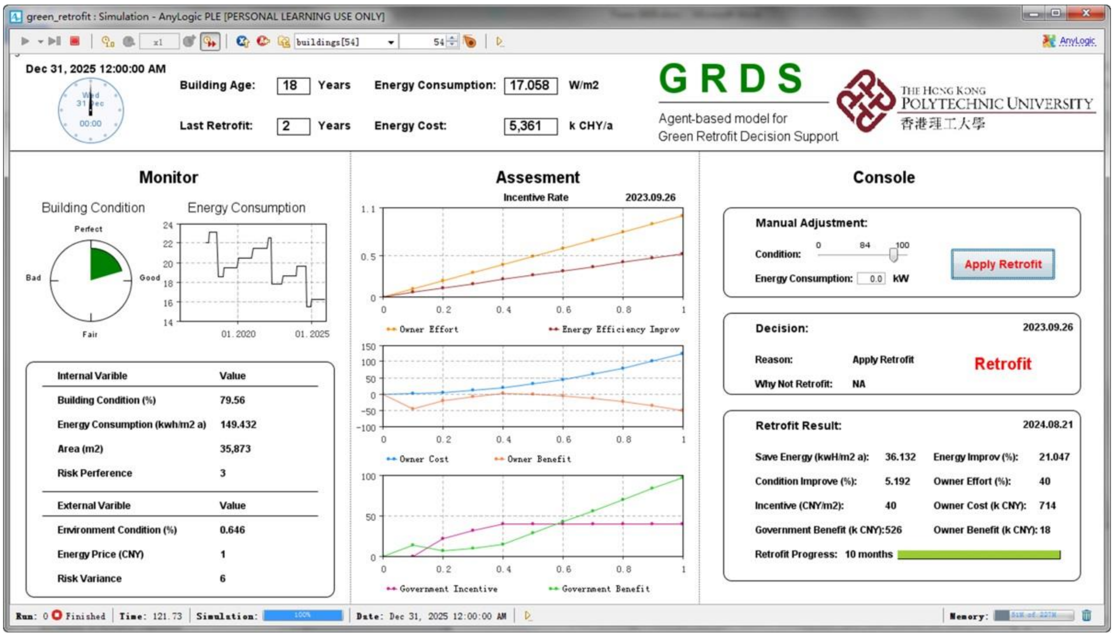


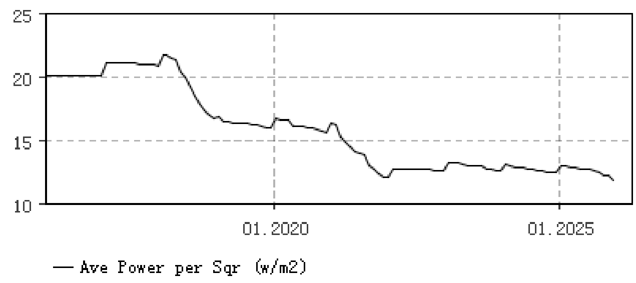
Figure 7.24 Screen capture of scenario 3 (policy of Shenzhen)

The configurations of the three scenarios are the same at the starting point. Under different policies, the agents in the simulation have different actions to optimize their benefits. After simulating a decade of time elapse, the results of the three scenarios are shown in Table 7.2. The changes of electric power per square meter during the simulated time are shown in Figure 7.25, which illustrates the energy saving effect.

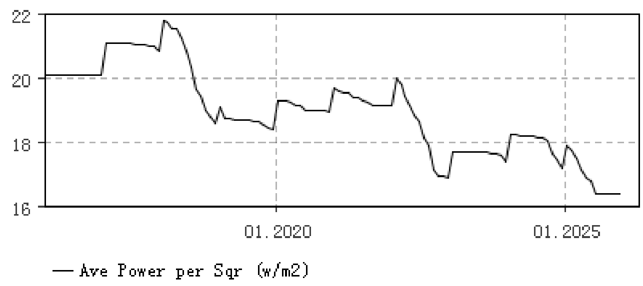
Table 7.2 Simulation results of the three scenarios

Simulation Results	**Proposed**	**Shanghai**	**Shenzhen**
(a) Incentive (M CNY)	169	366	360
(b) Efficiency Improvement (%)	39	15	14
(c) Cost of Owner (M CNY)	351	234	233
(d) Total Energy Save (MWh)	1,589,616	434,051	423,024
(e) Improvement per Incentive (b)/(a)	0.231	0.039	0.041
(f) Improvement per Total Cost (b)/((a)+(c))	0.075	0.024	0.025
(g) Energy Save per Total Cost (d)/((a)+(c))	3057	713	723

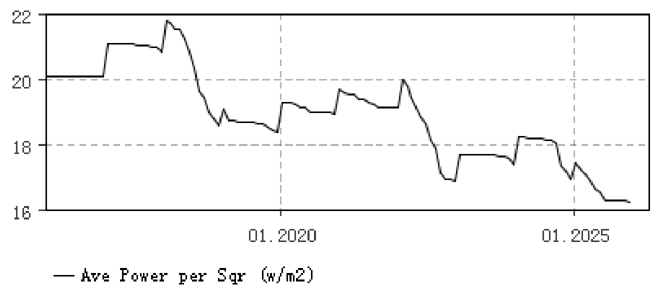
The simulation results show that the proposed model has the best effect of green retrofit. Compared to the other two scenarios, the efficiency improvement in 10 years is more than two times, and the energy saving per total cost (cost of both government and owners) is more than four times. Under all criteria, the performance of the proposed model is much better than that of the policies of Shenzhen and Shanghai. The results of the Shanghai and Shenzhen policies are almost the same.



(a)



(b)



(c)

Figure 7.25 Change of electric power per square meter during simulation for 10 years:

(a) the proposed model, (b) Shanghai, and (c) Shenzhen.

7.6.3 Sensitivity analysis

The sensitivity analysis is illustrated in this section to test the sensitivity of the proposed model to different variables.

Cost Coefficient

Figure 7.26 shows the sensitivity analysis of the cost coefficient of owner. The results indicate that, in the proposed model, the government incentive increases slightly when the cost coefficient is below 150, and nearly maintains invariability when the cost coefficient is beyond 150. In the Shanghai and Shenzhen scenarios, the incentive of government monotonically decreases with the cost coefficient. This means that when the cost of green retrofit increases, the incentive of government will decrease under the Shanghai and Shenzhen policies, but will nearly be a constant in the proposed model. Specifically, the proposed model is not sensitive to the cost coefficient, but the other two are sensitive to this variable.

The figure on top left shows that, in all three scenarios, the cost of green retrofit is negatively correlated with the cost coefficient, because the higher the cost coefficient, the less effort will be paid by owners. The cost of green retrofit in the proposed model is always higher than the other two, indicating that the effort of owners is higher.

The figures on the bottom show that, in all three scenarios, the energy efficiency improvement and the energy savings are negatively correlated with the cost coefficient, which indicates that the higher cost coefficient of green retrofit will hinder the energy savings.

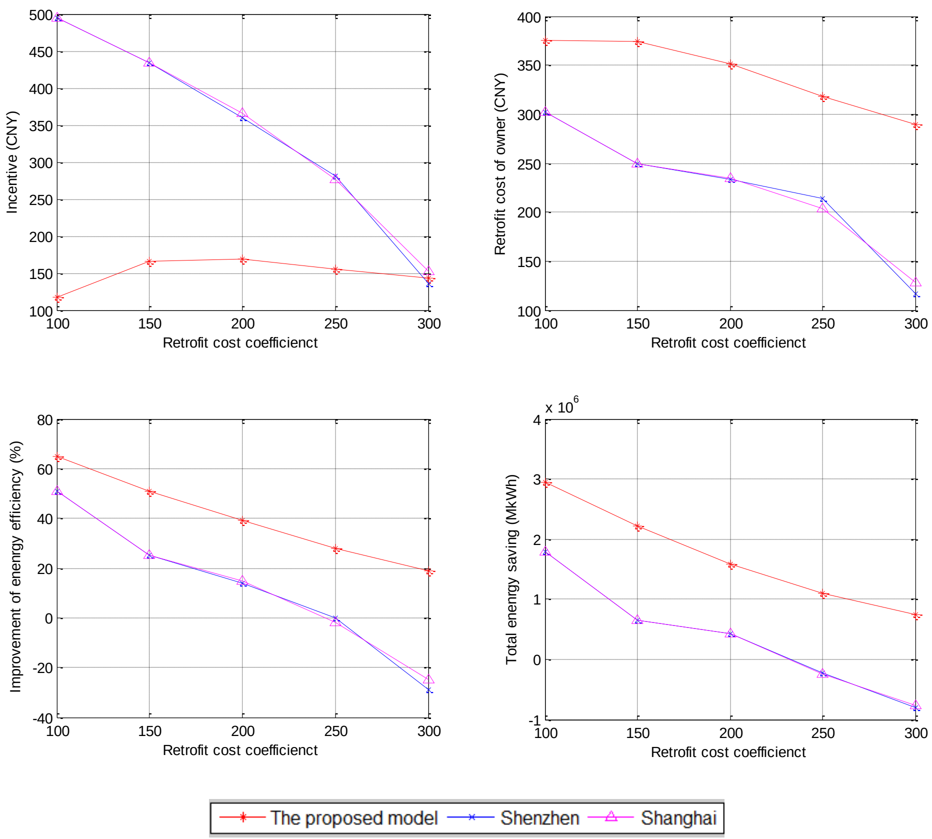


Figure 7.26 Sensitivity analysis of the cost coefficient

Technology Development

Figure 7.27 shows the sensitivity analysis of technology development. The results indicate that, in the proposed model, the incentive of government increases slightly when the technology development coefficient is below 0.5, and increases slightly when the technology development coefficient is beyond 0.5. In the Shanghai and Shenzhen scenarios, the incentive of government increases sharply with the technology development when the technology development coefficient is below 0.5, and decreases slightly when the technology development coefficient is beyond 0.5. This means that when technology development is slow, the incentive of government is sensitive under the Shanghai and Shenzhen policies. By contrast, when technology development is fast, the incentive of government is not sensitive under the Shanghai and Shenzhen policies. The proposed model is not sensitive to technology development, nearly keeping a constant value.

The figure on the top left shows that, in the Shanghai and Shenzhen scenarios, the cost of the green retrofit is positively correlated with the cost coefficient. However, the cost of green retrofit in the proposed model increases first and then starts decreasing on the 0.5 inflection point. This means that the efforts of owners increase when the technology development is low, but when the technology is very high, owners do not need to pay high efforts to achieve the optimal results.

The figures on the bottom show that, in all three scenarios, the energy efficiency improvement and the energy savings are positively correlated with the technology development, indicating that the higher technology development of green retrofit will improve the energy savings. Specifically, the technology improvement is very important to green retrofit and energy saving.

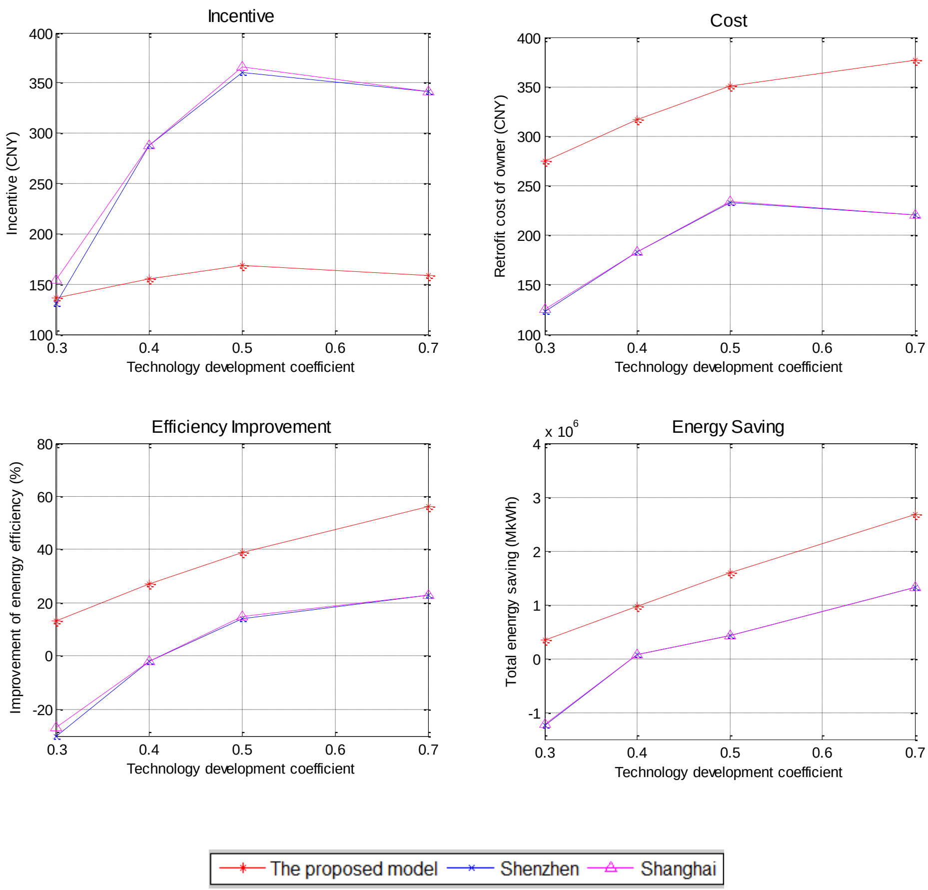


Figure 7.27 Sensitivity analysis of technology development

Risk

Figure 7.28 shows the sensitivity analysis of risk. The results indicate that in the proposed model, the government incentive is essentially constant when the variance of uncertainty is below 1, and decreases significantly when the variance of uncertainty is beyond 1. In the Shanghai and Shenzhen scenarios, the incentive of government increases slightly with the risk when the variance of uncertainty is below 0.5, decreases sharply when the variance of uncertainty is between 0.5 and 1, and keeps to zero when the variance of uncertainty is beyond 1. This indicates that the incentive of government is sensitive to risk under the Shanghai and Shenzhen policies, and if the risk is too high the incentives of government are useless. The incentive of government is not sensitive under the Shanghai and Shenzhen policies. The proposed model is less sensitive to risk, and when risk is high, an optimal solution of incentive is still found.

The figure on the top left shows that, in the Shanghai and Shenzhen scenarios, the cost of green retrofit drops sharply when the variance is below 1 and keeps to zero when the variance is beyond 1. The cost of green retrofit in the proposed model decreases slowly with risk. This means that the higher the risk, the lower the effort of owners in the proposed model, but the optimal effort of the owners is not sensitive to risk. However, the cost of green retrofit in the other two scenarios is very sensitive to risk.

The figures on the bottom show that the trends of the energy efficiency improvement and the energy savings are similar to the trends of cost, indicating the higher risk of the lower effect of green retrofit. In addition, the policies of Shenzhen and Shanghai are very sensitive to risk.

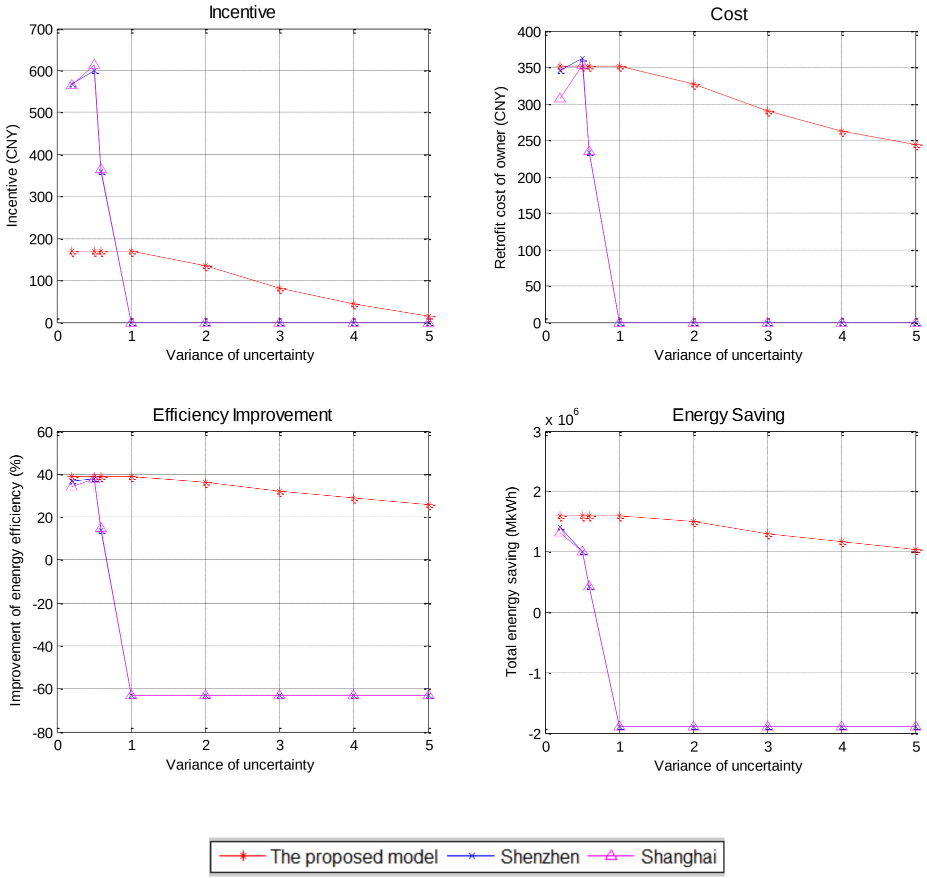


Figure 7.28 Sensitivity analysis of risk

Environment Condition

Figure 7.29 shows the sensitivity analysis of the environment condition. The results indicate that, in the proposed model, the incentive of government decreases with the environment condition. This means that the better the environment condition, the less the government incentive. In the Shanghai and Shenzhen scenarios, the incentive of government is a constant with different environment conditions. This indicates that the incentive of government does not change with the environment condition under the Shanghai and Shenzhen policies. Regardless of the environment condition, the incentive is the same. The incentive in proposed model is much less than the other two policies when the environment condition is good.

The figure on the top left shows that, in the Shanghai and Shenzhen scenarios, the cost of green retrofit remains the same with the environment condition. The cost of green retrofit in the proposed model decreases slowly with the environment condition. This means the better the environment condition, the lower the effort of owners in the proposed model.

The figures on the bottom show that the trends of the energy efficiency improvement and the energy savings are similar to the trends of cost, indicating that the better the environment condition, the lower the effect of green retrofit. Furthermore, the policies of Shenzhen and Shanghai are the same in different environment conditions.

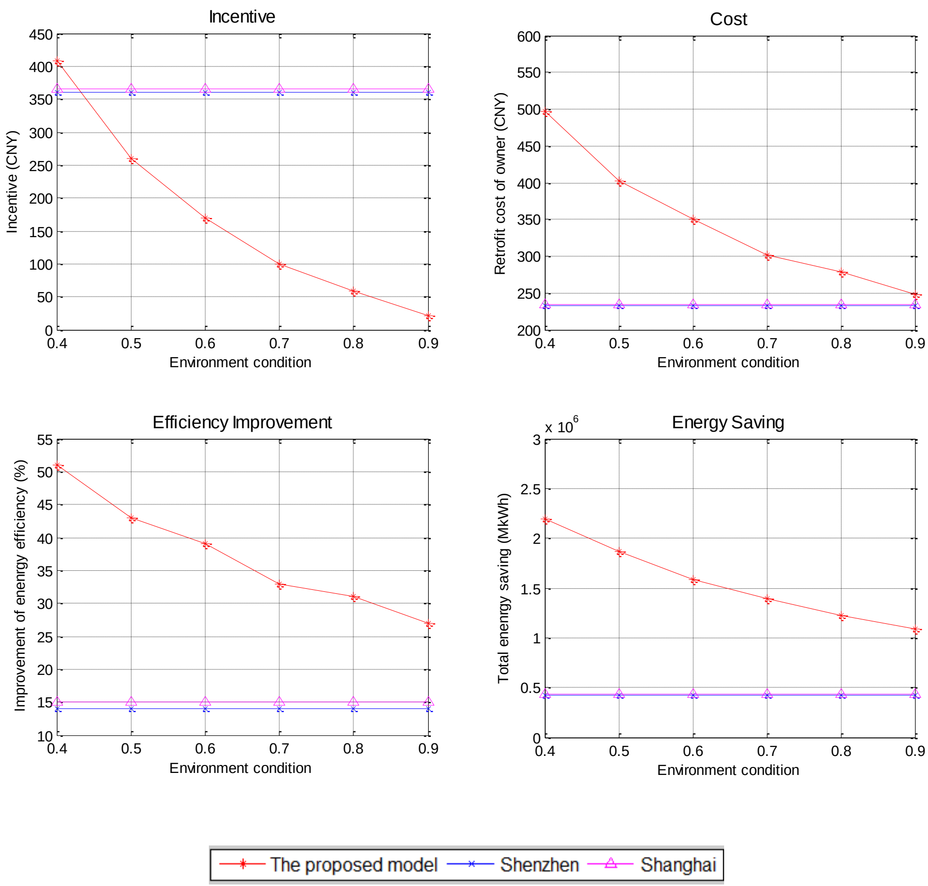


Figure 7.29 Sensitivity analysis of environment condition

Risk Preference

Figure 7.30 shows the sensitivity analysis of risk preference. The results indicate that, in the proposed model, the incentive of government decreases slightly with the degree of risk aversion. This means the higher the degree of risk aversion, the less the government incentive, but the changes are not very significant. In the Shanghai and Shenzhen scenarios, the incentive of government changes significantly with the risk preference. In the Shanghai and Shenzhen scenarios, the incentive of government decreases sharply when the risk aversion coefficient less than 10, and keeps to zero when the risk aversion coefficient is more than 10. This means if the owners are highly risk averse, the government incentive cannot have effect.

The figure on the top left shows that, in the Shanghai and Shenzhen scenarios, the cost of green retrofit drops sharply when the risk aversion coefficient is below 10 and keeps to zero when the risk aversion coefficient is beyond 10. The cost of green retrofit in the proposed model decreases slowly with risk aversion. This means that the higher the risk aversion, the lower the effort of owners in the proposed model, but the optimal effort of owners is not sensitive to risk aversion. The cost of green retrofit in the other two scenarios is very sensitive to risk.

The figures on the bottom show that the trends of the energy efficiency improvement and the energy savings are similar to the trends of cost, indicating that the higher the risk aversion, the lower the effect of green retrofit. The policies of Shenzhen and Shanghai are also very sensitive to risk aversion.

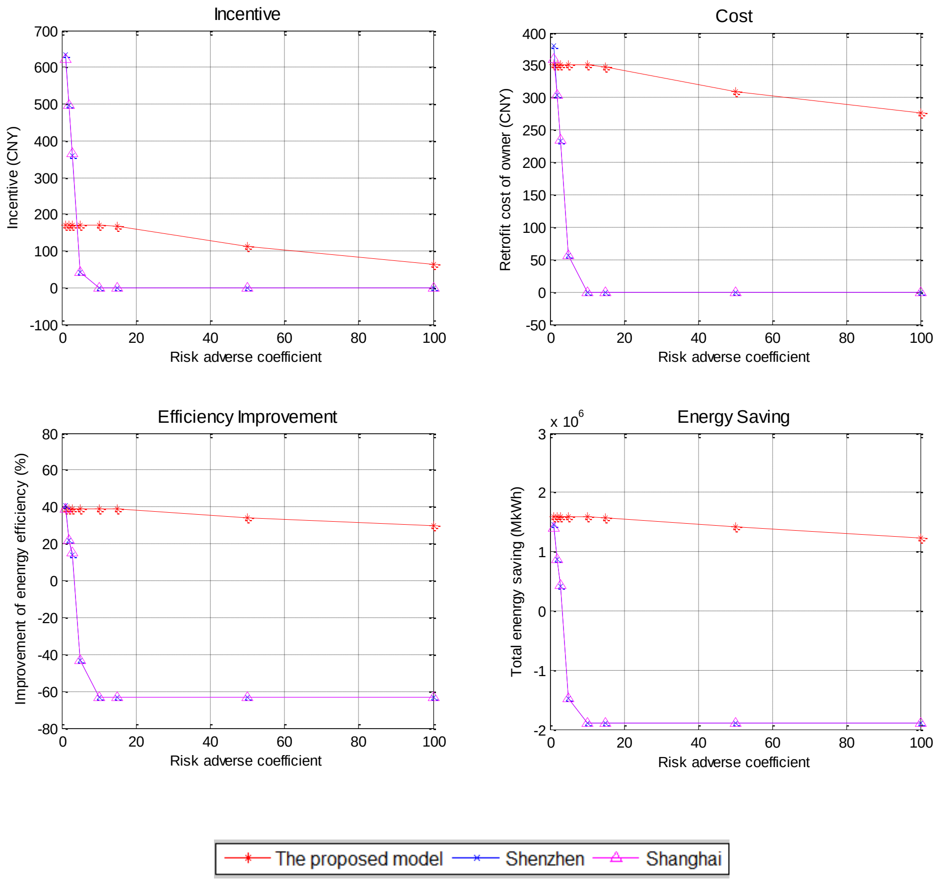


Figure 7.30 Sensitivity analysis of risk preference

Acceptable Threshold

Figure 7.31 shows the sensitivity analysis of the acceptable threshold. The results indicate that, in the proposed model, the incentive of government decreases slightly with the acceptable threshold. This means that the higher the acceptable threshold, the less the government incentive but the changes are not very significant. In the Shanghai and Shenzhen scenarios, the incentive of government decreases significantly with the acceptable threshold. The incentive of government is higher than that of the proposed model when the acceptable threshold is less than 0.05 and lower when the acceptable threshold is more than 0.05. This means that if the threshold of owners is high, then the incentive of government in the proposed model will be higher, and vice versa.

The figure on the top left shows that, in all three scenarios, the cost of green retrofit is negatively correlated with the acceptable threshold and the slopes are similar. This means that the higher the threshold, the less effort the owners will pay on green retrofit. The sensitivity of cost is similar in these three scenarios.

The figures on the bottom show that the trends of the energy efficiency improvement and the energy savings are similar to the trends of cost, indicating that the higher the threshold, the lower the effect of green retrofit. Additionally, the policies of the three scenarios are sensitive to risk aversion.

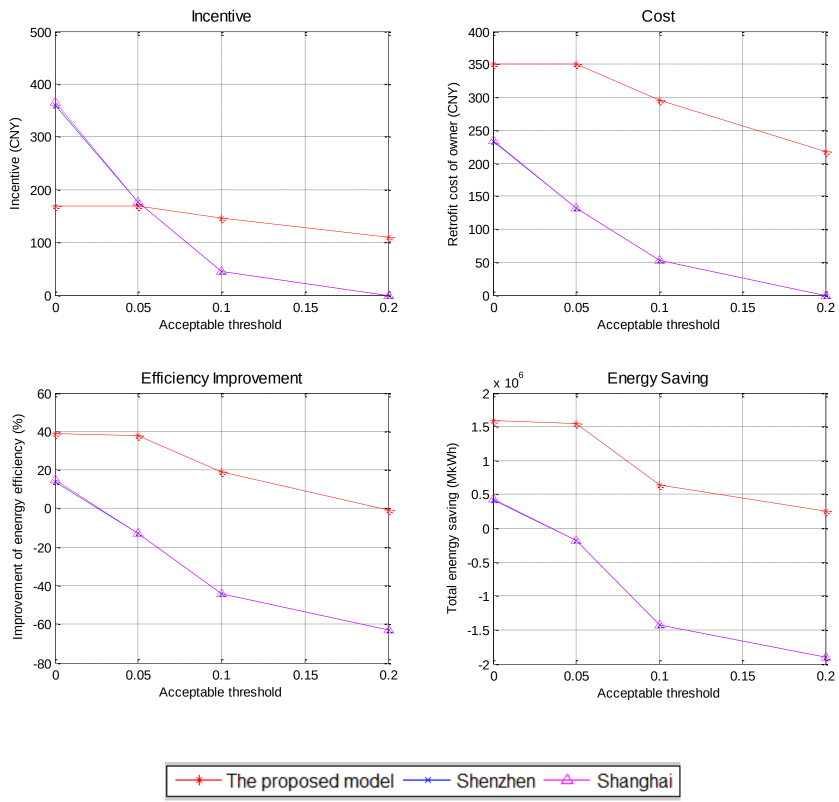


Figure 7.31 Sensitivity analysis of acceptable threshold

Energy Price

Figure 7.32 shows the sensitivity analysis of the energy price. The results indicate that, in the proposed model, the incentive of government decreases significantly with the energy price. This means that the higher the energy price, the more the government incentive. In the Shanghai and Shenzhen scenarios, the incentive of government increases more significantly with the energy price. This means that the incentive of government is more sensitive to energy price under the Shanghai and Shenzhen policies.

The figure on the top left shows that, in all three scenarios, the cost of green retrofit is positively correlated with the energy price. This means that the higher the energy price, the more effort owners will pay on green retrofit, because a high energy price can improve the benefit of green retrofit.

The figures on the bottom show that the trends of the energy efficiency improvement and the energy savings are similar to the trends of cost, indicating that the higher the energy price, the better the effect of green retrofit. The policies of the three scenarios are also sensitive to energy price.

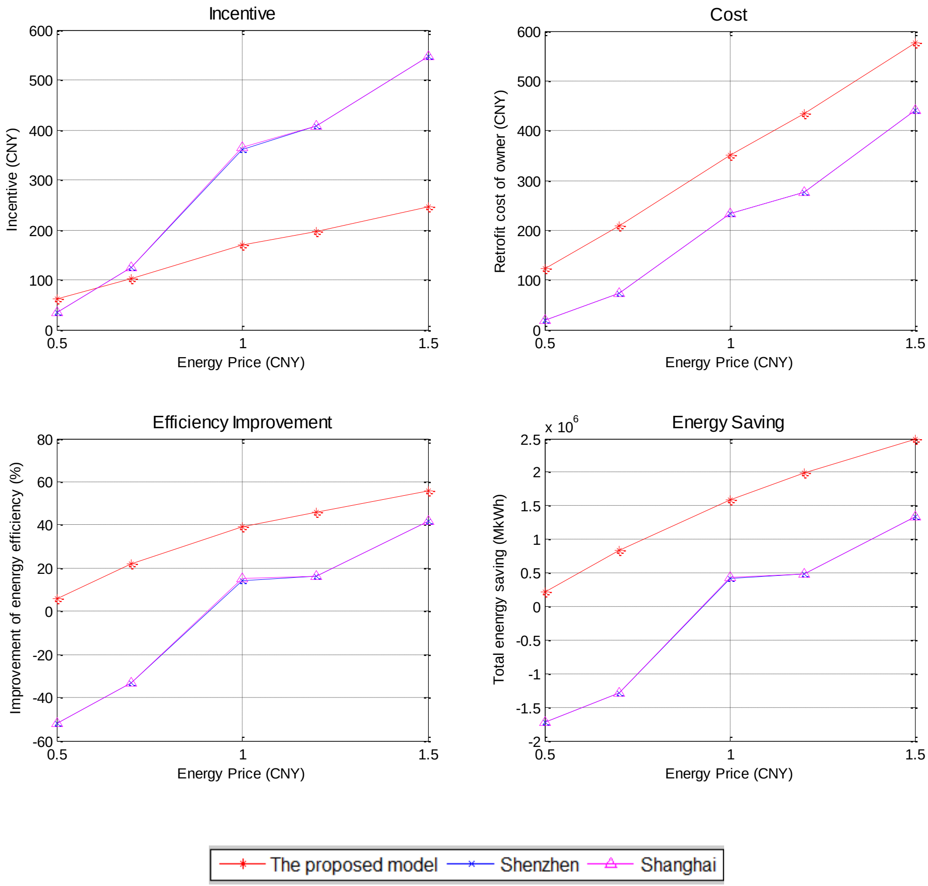


Figure 7.32 Sensitivity analysis of energy price

7.7 Summary of the Chapter

The theoretical analysis in Section 6 deduced the relationship among stakeholders (i.e., owner, tenant, and government) for one building. To provide decision supports for green retrofit, an agent-based platform for green retrofit was designed and illustrated in this chapter.

The platform has five layers, namely, user layer, agent layer, application layer, logic layer, and hardware layer. Each layer was introduced in detail. The platform was modularized and loosely coupling, which gave the system flexibility and expansibility. According to the different applications, the agent-based platform for green retrofit decision-making support has two application levels: the building level and the city level. The former is mainly for decision making on individual green retrofit projects, and the latter is mainly for the policies suggestions in a city.

The attributes of agent were defined, and the interactions among agents were introduced. There are four agents in this platform, namely, owner, tenant, government, and building. Each agent has its own attributes and interactions with other agents. The activities of agents follow their own state charts and corresponding rules. Each agent only makes decisions according to its own benefits.

Both Shanghai and Shenzhen are pilot cities of green retrofit for public buildings and are first-tier cities in China. This study applied the agent-based platform to simulate the proposed model (introduced in Section 6) and the policies of Shanghai and Shenzhen as three scenarios. The results showed the proposed model performs much better than the other two. The sensitivity analysis showed the platform is robust.

Chapter 8 Conclusions

8.1 Introduction

This chapter summarizes the key research findings and suggests future research directions based on the limitations in this study. The research aim and objectives are first reviewed to examine whether they have been achieved. The key research findings are then summarized and the contributions to the existing knowledge are concluded. Finally, limitations and future research directions are discussed.

8.2 Review of Research Objectives

The buildings, especially the public buildings played an essential role in total energy consumption and greenhouse gas emission. The energy consumption in the operation phase is much higher than that in the construction phase during a life cycle of a building. Therefore, improving the energy efficiency of existing public buildings is critical for reducing energy consumption and GHG emission. Since the green retrofit for existing buildings is a potential way to improve the energy efficiency of existing buildings, the governments of numerous countries tried to stimulate the market of green retrofit by various policies. Although green retrofit is emphasized by governments, green retrofit projects have not been well developed in the industries.

Most previous studies investigated the green retrofit from the technical, economic, and environmental perspectives. Very few studies, if not none, have investigated the decision-making behaviors of the key stakeholders and their different relationships under different circumstances. Therefore, this study intended to answer the research questions: "What are the behavior strategies of stakeholders in decision making on green retrofit?" and "How to improve decision making on green retrofit through modelling their behaviors?".

The primary aim of this research is to examine whether an agent-based platform that models decision-making behaviors of stakeholders can support decision making on green retrofit of public buildings.

The specific objectives of this research are as follows:

(1) To analyze the relationship of stakeholders and their priorities in green retrofit through a two-mode social network analysis.

(2) To build a model of decision-making behaviors based on game theory for optimizing decisions of key stakeholders on green retrofit.

(3) To develop and validate an agent-based platform on the basis of the proposed model to support decision making on green retrofit.

Chapter 2 and 3 are literature review serving as a theoretical foundation and solid reference for further in-depth analysis. Chapter 2 investigated the stakeholders and their characteristics, including their drivers and barriers of green retrofit. Chapter 3 identified the state-of-the-art studies of MASs focusing on consensus issues. To achieve Objective 1, Chapter 5 investigated the stakeholder relationship and priority through a two-mode social network analysis. The findings of this chapter also provided the key stakeholders who are focused on in the next steps. To achieve Objective 2, the game model of key stakeholders was built in Chapter 6 to study the decision strategies of stakeholders under different circumstances, as well as identify the optimal solutions of government policies. To achieve objectives 3, Chapter 7 developed an agent-based platform for decision-making support at both building level and city level. A comparative study was conducted to analyze the policies for promoting green retrofit of public buildings launched by the Shanghai and Shenzhen local government, which validated the effectiveness of the proposed platform. Based on this platform, the efficiency of decision making on green retrofit can be promoted.

8.3 Summary of Research Findings

The key findings of this study are highlighted as below.

First, a two-mode network of stakeholders was developed to analyze the interrelation and priority of stakeholders in green retrofit projects. According to the similarity of stakeholders' influence on the success of green retrofit projects, the stakeholders were classified into five clusters: cluster 1 (owner/client, property manager, tenant/user), cluster 2 (supplier, contractor, sub-contractor), cluster 3 (government, energy service company, designer, research institution), cluster 4 (financial institution/ bank), and cluster 5 (industry association, NGO/community). The classification can help decision makers understand the relationship among stakeholders.

Owner, property manager, designer, and government are the four most important stakeholders in green retrofit. Research institutions, industry associations, and NGO/community are the three least important stakeholders, who neither directly participant in the green retrofit projects nor have a direct economic interest from green retrofit projects. Specifically, the values of the last two stakeholders are significantly below those of the others, indicating that they are only in a peripheral position within the stakeholder circle.

Based on the analysis results, tenants were underestimated in the previous stakeholder analysis. Tenants are direct users of the buildings, who are in the same cluster with clients as a core stakeholder, but only in the medium position in the priority rank of stakeholders. Green retrofit may influence the tenants in various aspects, while occupants can also significantly influence the success of green retrofit projects. However, previous studies as well as stakeholders in practical projects underestimated the influence of tenants on the success of green retrofit. Therefore, additional attention should be paid on the tenants in green retrofit projects.

Second, a game theory-based model was built, which can explain the reasons for stakeholder behaviors in green retrofit and can optimize the decision making on green retrofit by balancing benefits among key stakeholders. Based on the game model, without government incentive, the Nash equilibrium for the owner and the tenants is "reluctant to retrofit" and "reluctant to retrofit" respectively, under both single-occupied and multi-occupied conditions. The results of the game model explain the lack of enthusiasm for green retrofit in the industry.

The split incentives between owners and tenants are identified as main barriers of making green retrofit decisions. The owners usually invest in green retrofit projects, but various benefits (e.g., energy saving, health, and productivity improvement, etc.) will be reaped by the tenants. This imbalance of interests hinders the cooperation among stakeholders and is an essential problem in green retrofit decisions. To overcome split incentives, optimized policies were launched to redistribute the profit of green retrofit among stakeholders, which can improve the implementation of green retrofit.

Based on the game model, the government should differentiate from incentive policies for different occupancy types of buildings. The characteristics of stakeholders under different building types are different. When the government makes incentive policies for different types, the utilities of owners and tenants can be maximized, and the total efficiency can be optimized. However, at present, most policies related to green retrofit have not differentiated these types. This is a reason why the policies for green retrofit are not efficient and have not achieved active responses from the industry.

In tenant-occupied buildings, the optimal incentives of government are in high uncertainty and are difficult to decide on, due to the complex relationship and uncertainty between owners and tenants. However, in reality, most public buildings are occupied by numerous tenants. This is a reason that green retrofit policies have not achieved satisfactory effects. Therefore, the proposed model can help understand the interrelations between owners and tenants, which is essential for the policy making of green retrofit.

Third, an agent-based platform for supporting decision making on the green retrofit of public buildings was developed based on the proposed model. On the basis of the experiment on the agent-based platform, the simulation results show that the proposed game model has the best performance of green retrofit compared to the existing policies for green retrofit of public buildings in Shanghai and Shenzhen. In the scenario using the proposed game model, the improvement of energy efficiency in 10 years is more than two times of that in the other scenarios, and the energy saving per total cost (cost of both government and owners) is more than four times. The results of the scenarios using Shanghai and Shenzhen policies are almost the same.

The sensitivity analysis shows that the proposed platform is robust to different influencing factors, including cost coefficient, technology development, risk, environment circumstance, risk preference, and energy price. The effects of the proposed model are more stable than other scenarios. The effects of green retrofit in the proposed model are the most sensitive to the two influencing factors (i.e., the cost of green retrofit and the energy price).

8.4 Contributions of the Research

8.4.1 Contributions to Knowledge

This study made original contributions to the knowledge of decision making for the green retrofit of public buildings in several aspects.

This study first applied a two-mode social network analysis to investigate relationship and priority of stakeholders in green retrofit. Two-mode networks are beneficial for analyzing the relationships between two objects. CSFs are introduced as intermediate variables to analyze influence of stakeholders on the success of projects. The relationship and priority of stakeholders can be revealed through the two-mode social network analysis. The analysis results can help understand the roles and behaviors of these decision makers.

This study made an original contribution to analyzing decision-making behaviors of key stakeholders through a game theory-based model. Previous studies mainly use survey methods to analyze decision making of stakeholders, but most stakeholders prefer to show their positive attitudes rather than their reluctance toward green retrofit to the public. Constrained by such realities, this study built the game theory-based model and applied logical deduction rather than used an empirical study. The analysis results of the game model revealed the reasons why owners are not initiative to green retrofit without incentive policies of government.

In the game model, this study first differentiated incentive policies for different building types and had much better performance than the traditional method. The interests of stakeholders are different under different occupancy types. Thus, this study analyzed the decision making on green retrofit in different building types. The results showed the behaviors of stakeholder are significantly different in different types. Therefore, the government should differentiate incentive polies for different building types.

8.4.2 Practical contributions to the industry

This study proposed an agent-based platform to support the decision making on green retrofit projects. The contributions of this platform in industry are in several aspects as below.

This platform is the first agent-based platform for decision-making support of green retrofit. At present, no electronic platform for green retrofit exists, and the information of each stakeholder and department are isolated. This study proposed an agent-based platform through modelling decision-making behaviors of stakeholders in green retrofit. The stakeholders are projected to agents in the platform and their decision-making behaviors can be simulated based on the proposed game theory-based model. The results of simulation can provide information to facilitate decision making and policy making.

The proposed platform can originally provide customized policy suggestions for different types of buildings. At present, the incentive policies are the same for all the buildings, which is known as “one-size-fits-all” policies. The proposed platform in this study can give different policy suggestions according to different types of buildings, which can improve the efficiency of policies and the effect of green retrofit.

The proposed platform is the first platform can be used by both the government and other stakeholders (e.g., owners, tenants and facility managers). For the government, the proposed agent-based platform can provide policy suggestions. The most efficient incentive policy can be calculated for different circumstances (e.g., environment condition, risk, energy price). For other stakeholders, the proposed platform can provide decision-making support for an individual green retrofit project (e.g., assessment of the benefit and cost of green retrofit, decision of whether to retrofit and select the most efficient plan). The different stakeholders in green retrofit can use the same platform, which can improve the collaboration among stakeholders and make the decision-making process more simple and transparent.

Based on this platform, this study first evaluated the factors influencing the decision making on green retrofit through simulation. Most previous studies evaluated influencing factors through empirical studies and econometric methods. The proposed platform can evaluate their influence on the decision making by simulation. This method can significantly save time and easily adapt to dynamic variables. The results of simulation can provide real-time suggestions to the government. For example, the incentive rate and the effect of green retrofit are sensitive to energy price. Therefore, when energy price fluctuates significantly, the government will be alerted to pay more attention on the green retrofit market and adjust the policies in time.

In summary, the proposed agent-based platform is an effective tool to assess costs and benefits of green retrofit projects, support decision making and provide policy suggestions, and consequently, it can further promote green retrofit of public buildings and reduce energy consumption and GHG emission.

8.5 Limitations of the Research

This study has some limitations. First, the data used in stakeholder analysis are limited. For practical reasons, the case study used classical experience-based methods to identify CSFs and stakeholders. The number of experts was limited. In addition, the focus group meeting for SNA was a one-off. To get more general results, the proposed method should be applied in more focus group meetings so that results could be reviewed and compared to improve the understanding on CSFs of energy efficiency retrofit.

Second, this study is mainly a theoretical study with logical deduction rather than an empirical study. This limitation is caused by a lack of effective data and real cases to model the behaviors of owners and tenants in green retrofit. Although several case studies were conducted to verify the theoretical model in this study, it still lacked the support of survey data by empirical study.

Third, the proposed agent-based platform was not applied for a real case of decision making or policy making to verify it. Since the platform is mainly for policy optimization, it needs data in a city scale. The data from only one building or several buildings is not sufficient to validate the platform. Although many cities in mainland China developed energy audit systems for public buildings, the data is confidential to public for the time being. So it is very difficult to use real data to validate the platform at present. The agent-based platform in this study is a prototype, which has not reached the commercial software standard and has not been applied in real projects. Thus, there should be some further improvement in real projects.

8.6 Future Research

Future research related to stakeholder analysis in green retrofit can be undertaken in two directions. First is improving the analysis methods for the two-mode networks to enhance the proposed models, and the other is conducting more case studies to obtain more concrete results. This two-mode network model can similarly be applied to other research topics in project management to analyze the relationship of two groups.

Note that this study assumes a static game analysis, which is useful to understand the underlying logic and optimal decisions. However, green retrofit is undertaken in a dynamic world. Therefore, future studies should use a dynamic game analysis to model the decision behaviors of owners and tenants to further deepen our understanding. One assumption of game theory is that the players are rational, which means their decision-making behaviors are only based on economic benefit. But in real world, behaviors of stakeholders are not completely rational. For example, the decision could be influenced by emotion. So the future studies can explore the behaviors not related to economics.

At the present stage of the platform, the agents cannot learn from each other. It could be a future study that the agents can learn from each other. For example, the owner agents can observe that other owners got benefits from green retrofit, and they will learn to have green retrofit. The number of stochastic attributes defined in this model is limited and cannot represent all the characteristics of the stakeholder behaviors. The proposed platform is a prototype which demonstrated that the MAS can model the decision-making behaviors of stakeholders and improve the decision making on the green retrofit. In future studies more attributes of stakeholder behaviors can be modeled on the proposed platform.

The proposed agent-based platform should be applied in real projects by the government and other stakeholders. Some pilot studies can be conducted in some cities, for example, Shanghai and Shenzhen, which are pilot cities for green retrofit of public buildings. Many cities in mainland China developed energy audit systems for public buildings. For example, Shenzhen developed energy audit system for public buildings in 2009. Although the data is confidential to public for the time being, it is possible to use the data through cooperation with government in future studies. Then the real data can be used to validate the platform. The comments of users can also be collected to help improve the platform in the future.

Appendix I: The Document Used in the Focus Group Meeting for Social Network Analysis

既有商业建筑绿色改造协同设计的调查研究

诚邀阁下参与由香港理工大学建筑与房地产学系开展的一项学术调研活动。本次调研的宗旨为分析并寻求**既有商业建筑绿色改造协同设计中不同利益相关者与关键成功因素的关系研究**。其中**"既有建筑绿色改造"是指：对既有建筑进行节能，环保，低碳，新能源接入等改造，涵盖建筑结构，外墙，设备，材料，能源系统，自动化控制等方面**。填写本次访谈大约需要 1-2 小时，问题没有对错之分，仅代表您的个人看法。所有结果都将保密并作匿名处理。如果阁下有任何疑问或顾虑，请联系本项目负责人：香港理工大学建筑与房地产学系梁昕，邮箱地址为：xin.c.liang@ 。或联系香港理工大学学术委员会咨询相关学术道德规范。我们非常感谢您对本次调查做出的贡献！

既有商业建筑绿色改造协同设计的调查研究

第一部分 基本信息

序号	您的职业或在绿色改造项目中的角色*	您从事本行业的时间	您接触既有商业建筑绿色改造的时间
1.			
2.			
3.			
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10.			

注*：本栏可以填写业主/楼宇所有者，租户，物业公司/运维管理方，设计方，施工方，供应商，分包方，政府部门，财务机构（银行，信托等），能源服务公司，行业团体（建筑协会等），民间社团（环保社团等），学术机构（高校，研究院等）或其他（请具体注明）。

第二部分 绿色改造的在协同设计方面的利益相关者与设计过程的关系

2.1. 基于您在**实际项目**中的经历及**个人认知**，请对以下既有商业建筑绿色改造**协同设计**的不同阶段**关键利益相关者**重要程度进行打分，即哪些利益相关者您认为对于协同设计的影响较大。

请在表格空白处填入 1-5，分别代表各阶段利益相关者的重要程度，其中数字代表：**1-非常不重要；2-不重要；3-一般；4-重要；5-非常重要**

既有建筑绿色改造的利益相关者	前期评估阶段	项目准备阶段	项目实施阶段	项目收尾阶段
1) 业主/楼宇所有者				
2) 租户				
3) 物业公司/运维管理方				
4) 设计方				
5) 施工方				
6) 供应商				
7) 分包方				
8) 政府部门				
9) 财务机构（银行，信托等）				
10) 能源服务公司				
11) 行业团体（建筑协会等）				
12) 民间社团（环保社团等）				
13) 学术机构（高校，研究院等）				
其他您认为需要补充的重要利益相关者				
14) 请补充：________________				
15) 请补充：________________				

第三部分 绿色改造的在协同设计方面的利益相关者与关键成功因素的关系

2.1. 基于您在**实际项目**中的经历及**个人认知**，请对以下既有商业建筑绿色改造<u>**协同设计**</u>的<u>**关键利益相关者**</u>对于<u>**关键成功因素的**</u>重要程度进行打分，即哪些利益相关者您认为对于关键成功因素的影响较大。

请在表格空白处填入 1-5，分别代表各阶段利益相关者的重要程度，其中数字代表：**1-非常不重要；2-不重要；3-一般；4-重要；5-非常重要**

既有建筑绿色改造的关键成功因素	业主/楼宇所有者	租户	物业公司/运维管理方	设计方	施工方	供应商	分包方	政府部门	财务机构（银行，信托等）	能源服务公司	行业团体（建筑协会等）	民间社团（环保社团等）	学术机构（高校，研究院等）
经济因素													
1) 可以承受的改造成本													
2) 由谁进行改造投资													
3) 节能的收益在利益相关者间如何分配													
4) 改造期间对正常运营的经济影响													
5) 利率/贴现值													

既有建筑绿色改造的关键成功因素	业主/楼宇所有者	租户	物业公司/运维管理方	设计方	施工方	供应商	分包方	政府部门	财务机构（银行，信托等）	能源服务公司	行业团体（建筑协会等）	民间社团（环保社团等）	学术机构（高校，研究院等）
6) 租赁类型（业主自用，单一租户，多租户共用）													
7) 能源账单支付类型（业主支付，租户支付，其他方支付）													
8) 政府补贴及税费减免													
9) 改造后租金是否上涨													
建筑信息及环境因素													
10) 建筑外部环境（地理位置、温度、湿度、日照条件、气候变化等）													
11) 建筑结构情况（建筑规模，结构，材料，开窗率，朝向等）													
12) 建筑设备情况（空调，新风，照明，													

既有建筑绿色改造的关键成功因素	业主/楼宇所有者	租户	物业公司/运维管理方	设计方	施工方	供应商	分包方	政府部门	财务机构（银行，信托等）	能源服务公司	行业团体（建筑协会等）	民间社团（环保社团等）	学术机构（高校，研究院等）
暖通等系统）													
13) 是否有完善并且电子化的建筑信息（如 BIM，CAD 图等）													
14) 较为准确的建筑监控与评估系统（建筑能耗、采光、设备老化等）													
社会及人文因素													
15) 具有共同且清晰的愿景													
16) 利益相关者之间协同合作													
17) 利益相关者之间的信息共享													
18) 用户的行为与需求的差异（能源使用行为等）													
19) 项目的组织管理（质量控制，进度													

既有建筑绿色改造的关键成功因素	业主/楼宇所有者	租户	物业公司/运维管理方	设计方	施工方	供应商	分包方	政府部门	财务机构（银行，信托等）	能源服务公司	行业团体（建筑协会等）	民间社团（环保社团等）	学术机构（高校，研究院等）
控制，风险控制等）													
20) 知识/经验分享与培训													
21) 社会文化与传统习惯影响（对于绿色，节能等概念的认同）													
技术因素													
22) 技术方案的成熟度													
23) 技术方案的复杂度													
24) 后期运维的可维护性													
25) 建筑信息化与计算机仿真能力													
26) 协同设计软件的成熟与自动化能力（设计过程，决策支持等）													

既有建筑绿色改造的关键成功因素	业主/楼宇所有者	租户	物业公司/运维管理方	设计方	施工方	供应商	分包方	政府部门	财务机构（银行，信托等）	能源服务公司	行业团体（建筑协会等）	民间社团（环保社团等）	学术机构（高校，研究院等）
政策及规范因素													
27) 明确的法律法规或政策指导													
28) 明确的建筑规程规范													
其他您认为需要补充的关键成功因素													
29) 请补充：____________													
30) 请补充：____________													

Appendix II: The Derivation Steps in the Game Model

$$\alpha^o + \beta^o k_{en}(a^o + a^t) + k_{ec}(a^o + a^t) - \frac{1}{2}b^t a^{t2} - \frac{1}{2}\rho\beta^{t2}\sigma^2 - \omega_0^t - \frac{1}{2}b^o a^{o2}$$
$$= \beta^o k_{en} a^t + k_{ec} a^t - \frac{1}{2}b^t a^{t2} - \frac{1}{2}\rho\beta^{t2}\sigma^2$$
$$= \beta^o k_{en}(\frac{k_{ec} + k_{ec}\beta^t}{b^t}) + k_{ec}(\frac{k_{ec} + k_{ec}\beta^t}{b^t}) - \frac{1}{2}b^t(\frac{k_{ec} + k_{ec}\beta^t}{b^t})^2 - \frac{1}{2}\rho\beta^{t2}\sigma^2$$
$$= \beta^o k_{en}(\frac{k_{ec}\beta^t}{b^t}) + k_{ec}(\frac{k_{ec}\beta^t}{b^t}) - \frac{1}{2}\frac{k_{ec}^2}{b^t}(\beta^{t2} + 2\beta^t + 1) - \frac{1}{2}\rho\beta^{t2}\sigma^2$$
$$= (-\frac{1}{2}\frac{k_{ec}^2}{b^t} - \frac{1}{2}\rho\sigma^2)\beta^{t2} + \beta^o k_{en}(\frac{k_{ec}\beta^t}{b^t})$$

$$\beta^t = (\frac{\beta^o k_{en} k_{ec}}{b^t}) / (\frac{k_{ec}^2}{b^t} + \rho\sigma^2) = \frac{\beta^o k_{en} k_{ec}}{k_{ec}^2 + \rho\sigma^2 b^t}$$

$$E(U^g) = E(\pi_{en} - \alpha^o - \beta^o \pi_{en}) = E(-\alpha^o + k_{en}(1-\beta^o)(a^o + a^t))$$

$$\max_{\beta^0} E(U^g) = \max_{\beta^0}(-\alpha^o + k_{en}(1-\beta^o)(a^o + a^t))$$

$$-\alpha^o + k_{en}(1-\beta^o)(\frac{\beta^o k_{en}}{b^o} + \frac{k_{ec}}{b^t} + \frac{k_{ec}}{b^t}\cdot\frac{\beta^o k_{en} k_{ec}}{k_{ec}^2 + \rho\sigma^2 b^t})$$
$$= -\alpha^o + k_{en}[(\frac{k_{en}}{b^o} + \frac{k_{ec}}{b^t}\cdot\frac{k_{en}k_{ec}}{k_{ec}^2 + \rho\sigma^2 b^t})\beta^o - (\frac{k_{ec}}{b^t}\beta^o) - (\frac{k_{en}}{b^o} + \frac{k_{ec}}{b^t}\cdot\frac{k_{en}k_{ec}}{k_{ec}^2 + \rho\sigma^2 b^t})\beta^{o2}]$$

$$\beta^o = [(\frac{k_{en}}{b^o} + \frac{k_{ec}}{b^t}\cdot\frac{k_{en}k_{ec}}{k_{ec}^2 + \rho\sigma^2 b^t}) - (\frac{k_{ec}}{b^t})] / 2(\frac{k_{en}}{b^o} + \frac{k_{ec}}{b^t}\cdot\frac{k_{en}k_{ec}}{k_{ec}^2 + \rho\sigma^2 b^t})$$
$$= \frac{1}{2} - (\frac{k_{ec}}{b^t}) / 2(\frac{k_{en}}{b^o} + \frac{k_{ec}}{b^t}(\frac{k_{en}k_{ec}}{k_{ec}^2 + \rho\sigma^2 b^t})$$
$$= \frac{1}{2}[1 - \frac{1}{(\frac{k_{en}b^t}{k_{ec}b^o} + (\frac{k_{en}k_{ec}}{k_{ec}^2 + \rho\sigma^2 b^t}))}]$$

$$\beta^o = \frac{1}{2}[1 - \frac{1}{(\frac{k_{en}b^t}{k_{ec}b^o} + (\frac{k_{en}k_{ec}}{k_{ec}^2 + \rho\sigma^2 b^t}))}]$$

Appendix III: The Key Functions in the Agent-Based Platform

// function for calculating incentives and related factors

```
int j = 0;

for (double i=0;i<=1;i=i+0.1)
{

double kec =
Building.Owner.Effort_Coe*Building.Energy_Consum_yearsqr*main.Energy_Price*
Building.Payback_Time;

double Effort = (kec + i*kec/(main.Env_Condition))/Building.Owner.Cost_Coe;

if (Effort>1)
{
Effort =1;
}

double Cost = 0.5*Building.Owner.Cost_Coe*pow(Effort,2);
double Incentive = i*kec/(main.Env_Condition)*Effort;
double risk = 0.5*Building.Owner.rou*pow(i,2)*pow(main.sigma,2);
double Owner_benefit = Incentive+kec*Effort-Cost-risk;
double Gov_benefit = (1-i)*kec/(main.Env_Condition)*Effort;
double Energy_Improv = Building.Owner.Effort_Coe*Effort;

if(Building.Need_Incentive==false)
{
if (Owner_benefit>0 && Gov_benefit>0)
{Building.Need_Incentive=true;}
}

Building.Risk[j]=risk;
Env_Benefit[j]=kec/(main.Env_Condition)*Effort;
Building.Owner.Rev[j]=kec*Effort;

Building.Effort_Set.add(i,Effort);
Building.Cost_Set.add(i,Cost);
Building.Owner_Benefit_Set.add(i,Owner_benefit);
Building.Incentive_Set.add(i,Incentive);
Building.Gov_Benefit_Set.add(i,Gov_benefit);
Building.Energy_Improv_Set.add(i,Energy_Improv);

j++;

}
```

// function for selecting optimal incentive under different strategies

```
max = 0;
maxi = 0;
// max government benefit
```

```
if (main.Strategy==0)
{

for (int i =0;i<11;i++)
{
if (Building.Owner_Benefit_Set.getY(i)>0 &&
Building.Gov_Benefit_Set.getY(i)>max)
{
max = Building.Gov_Benefit_Set.getY(i);
maxi = i;
}

}
Incentive_Rate = Building.Gov_Benefit_Set.getX(maxi);
Gov_Benefit_Optimal = Building.Gov_Benefit_Set.getY(maxi);
Building.Owner.Cost = Building.Cost_Set.getY(maxi);
Building.Owner.Benefit_Optimal = Building.Owner_Benefit_Set.getY(maxi);
Building.Owner.Effort = Building.Effort_Set.getY(maxi);
Incentive=Building.Incentive_Set.getY(maxi);
}

// fix energy improvement
if (main.Strategy==1)
{

for (int i =0;i<11;i++)
{
if (Building.Energy_Improv_Set.getY(i)>main.Threshold &&
Building.Gov_Benefit_Set.getY(i)>0 && Building.Owner_Benefit_Set.getY(i)>0)
{
maxi = i;
break;
}

}
Incentive_Rate = Building.Gov_Benefit_Set.getX(maxi);
Gov_Benefit_Optimal = Building.Gov_Benefit_Set.getY(maxi);
Building.Owner.Cost = Building.Cost_Set.getY(maxi);
Building.Owner.Benefit_Optimal = Building.Owner_Benefit_Set.getY(maxi);
Building.Owner.Effort = Building.Effort_Set.getY(maxi);
Incentive=Building.Incentive_Set.getY(maxi);
}

// max total benefit
if (main.Strategy==2)
{

for (int i =0;i<11;i++)
{
if (Building.Owner_Benefit_Set.getY(i)>0 &&
(Building.Gov_Benefit_Set.getY(i)+ Building.Owner_Benefit_Set.getY(i))>max)
{
max = Building.Gov_Benefit_Set.getY(i)+ Building.Owner_Benefit_Set.getY(i);
maxi = i;
}

}

Incentive_Rate = Building.Gov_Benefit_Set.getX(maxi);
```

```
Gov_Benefit_Optimal = Building.Gov_Benefit_Set.getY(maxi);
Building.Owner.Cost = Building.Cost_Set.getY(maxi);
Building.Owner.Benefit_Optimal = Building.Owner_Benefit_Set.getY(maxi);
Building.Owner.Effort = Building.Effort_Set.getY(maxi);
Incentive=Building.Incentive_Set.getY(maxi);
}


// shanghai
if (main.Strategy==3)
{

for (int i =0;i<11;i++)
{
if (Building.Owner_Benefit_Set.getY(i)>max)
{
max = Building.Owner_Benefit_Set.getY(i);
maxi = i;
}

}

Gov_Benefit_Optimal = Building.Gov_Benefit_Set.getY(maxi);
Building.Owner.Cost = Building.Cost_Set.getY(maxi);
Building.Owner.Benefit_Optimal = Building.Owner_Benefit_Set.getY(maxi);
Building.Owner.Effort = Building.Effort_Set.getY(maxi);
Incentive=Building.Incentive_Set.getY(maxi);
}



// shenzhen


if (main.Strategy==4)
{

for (int i =0;i<11;i++)
{
if (Building.Owner_Benefit_Set.getY(i)>max)
{
max = Building.Owner_Benefit_Set.getY(i);
maxi = i;
}

}

Gov_Benefit_Optimal = Building.Gov_Benefit_Set.getY(maxi);
Building.Owner.Cost = Building.Cost_Set.getY(maxi);
Building.Owner.Benefit_Optimal = Building.Owner_Benefit_Set.getY(maxi);
Building.Owner.Effort = Building.Effort_Set.getY(maxi);
Incentive=Building.Incentive_Set.getY(maxi);
}
```

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