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Application of System Dynamics in Understanding the Supply Chain of Building Sector: A Case Study in China

Xiaoying WU[1], Pei LIU[1,2,], Nici ZIMMERMANN[3], George PAPACHRISTOS[3], Borong LIN[1,4] *

1. Department of Building Science, School of Architecture, Tsinghua University, China

2. School of Business, Shandong University, Weihai, China

3. Institute for Environmental Design and Engineering, University of College London, United Kingdom

4. Key Laboratory of Eco Planning & Green Building, Ministry of Education, Tsinghua University, China

Abstract: It is well known that the building sector plays an essential role in China's total energy consumption and promoting green building could be one solution to reduce the energy consumption and overall emissions of greenhouse gases. In the whole supply chain of the building sector, there are various parties or stakeholders involved in, e.g. the developer, architect, engineers (mechanical/electrical/civil), contractor, consultants, facility company, owner etc. Thus, it becomes important to understand the relationships among these stakeholders, the mechanisms of motivations and initial barriers towards green buildings. This paper presents a case study of a building in the City of Shanghai with the highest rating in China's green building standard. The building integrates office and lab spaces.

Several stakeholders who worked on this office building project were interviewed, including staff from the developer, architect, engineer, facility manager and two users. The same set of interview questions were asked but modified according to the interviewee's background. Then, using a system dynamics approach, a causal loop diagram was built based on interview materials using Vensim®. The results are expected to produce a holistic picture of efficiently promoting green buildings in China by listing the locations of barriers along the supply chain and possible solutions. In the future, more case studies are going to be explored and comparison with buildings in the UK will be carried out.

Key words: System Dynamics; Supply Chain; Stakeholders; Green Buildings

1 Introduction

It is a common fact that the building sector plays an essential role in the total energy consumption and carbon emissions of China, and that the building sector accounts for as high as 43% of total energy consumption [1]. Therefore, saving energy and improving energy efficiency in the building sector becomes important. In order to achieve these targets, many solutions have been developed and tested, e.g. technologies to improve energy efficiency of HVAC systems, LED lighting, smart grid system, promoting natural ventilation, educating people to behave in efficient ways, using recyclable materials, integrated design, smart control systems, etc. However, almost all the existing solutions only focus on one or several parts of the building sector and ignore the rest. In order to improve the energy efficiency of the building sector, we should not simply add all energy efficient solutions and apply all of them to a single building. Instead, we should focus on the whole

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* Corresponding author at: Department of Building Science, School of Architecture, Tsinghua University, PR China. Tel.: +86 13910989594;
E-mail address: linbr@tsinghua.edu.cn

building market and try to reduce energy consumption from a holistic approach and in a systemic way. Thus, understanding the real green building market or the supply chain in the Chinese building sector becomes a key issue to be addressed.

1.1 Background

The building sector is made up of many stakeholders, including policy makers (government body), developers, architects, engineers (civil, mechanical and electrical), consultants, contractors (main and sub-contractors), material manufactures, facility managers and real users. Therefore, the idea of a "market of green buildings in China" needs to be shared by all stakeholders. Also, different people normally have different opinions about it depending on their occupation and experiences. Thus, it is necessary to map and present the ideas the key stakeholders hold and illustrate the links among them, to help us identify the important direct and indirect factors affecting the energy efficiency of buildings. In order to achieve this target, participatory system dynamics (SD) was used in this research project and is described in this paper. Participatory system dynamics   is a practical approach in system dynamics, with the aim to gain opinions from a group of interested parties and it can be described as engaging non-scientists in the scientific process [2].

1.2 What is System Dynamics (SD)

System dynamics (SD) was created by Professor Jay Forrester of the Massachusetts Institute of Technology (MIT) in the 1950s [3]. Initially SD was applied to solve corporate/managerial problems, and gradually researchers started to apply it to buildings. In 1995, Dyner used SD to model the residential sector and built a SD model to predict the future electricity consumptions [4]. Also, SD was integrated with life cycle cost (LCC) and life cycle carbon emission (LCCO2) to produce an optimized solution [5]. Furthermore, Mohamed integrated SD with LEED (Leadership in Energy and Environmental Design) to measure the sustainability of a residential building [6]. In addition, SD was engaged to analyze the effects of various potential policy if applied in building sector [7, 8]. Often, SD involves two important steps before simulation: plotting Causal Loop Diagrams (CLD) and generating Stock Flow Diagrams (SFD). CLDs are used to identify the relationships among the many related factors of a problem and SFDs are used for simulation. SD can also be used in a participatory manner with stakeholders, involving them in interviews and workshops for model building, improvement and validation [9, 10]. In this paper, SD was used to illustrate the move of the building sector supply chain in China towards sustainability.

2 Methodology

As shown in Fig 1, firstly six stakeholders from the green building project in Shanghai were interviewed by our research team, including two project managers, one architect, one engineer, one facility manager and one ESD (Environmentally Sustainable Design) consultant. That building was developed, designed and is used by their own company, so they also shared with us their options as users of that building. Each interview lasted about 40 minutes to one hour. Stakeholders were interviewed based on a same interview guide, but the focus differed slightly depending on their occupation. The interview materials were then imported into NVivo®, from which the key concepts that emerged in the interviews were extracted and summarized in nodes. Then the links between nodes were identified based on the interviews and plotted in Vensim®, thereby the first draft of a CLD was generated. The main purpose of developing CLD is to illustrate the causes and effects of

complicated problems in a simple manner. In a word, it is a qualitative analysis and provide support for further quantitative study, Stock-Flow simulation.

In order to make CLD representable for the building market of China, we held one workshop and invited about 50 people from the building industry including policy-makers, staff from real estate companies, environmentally sustainable design (ESD) consultants, architects, engineers and researchers. About 15 participants shared their feedback about the CLDs we developed and their own opinions about the supply-chain of buildings in China. This served the improvement and validation of the CLD and an amended CLD was produced. A stock-flow diagram is currently under developing and in the future a simulation model will be developed and the simulation results will be presented.
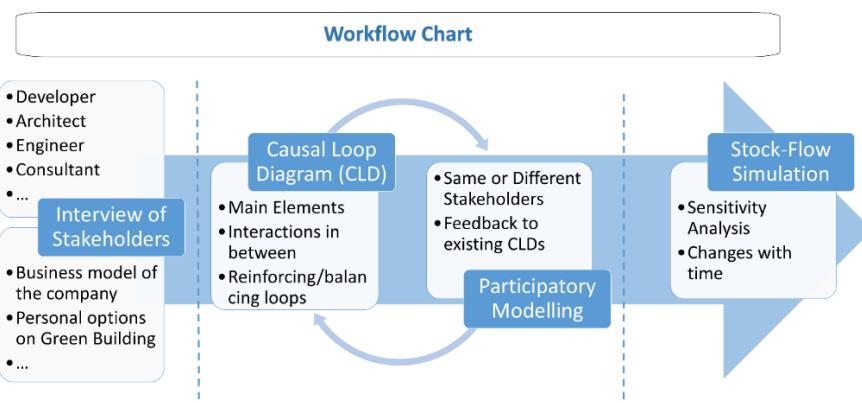
Fig 1 Flow chart of system dynamics in understating the supply chain of building in China

2.1 Development of Causal Loop Diagrams (CLD)

Fig 2 shows an excerpt of the interview materials and the nodes extracted in NVivo®. This excerpt is not generated by the software, instead it depends on the user. The causal links among all these key nodes were defined based on the interview materials as shown in Fig 3 (a), the first CLD. Normally CLDs may differ with different users and three main factors could affect this: their objectives, their knowledge of system dynamics and their knowledge of buildings. Different objectives will define a different structure of CLDs, thus the key nodes and causal loops will be different. Also the information received by the user from the interviewee really depends on the knowledge and experiences. Therefore, a validation process is required in order to decrease the subjective effects.

Fig 2 Example of nodes extracted from interview materials by NVivo®

2.1 Participatory System Dynamics Modelling

In order to amend and validate the draft CLD, participatory modeling was applied [11]. About 50 people from the building industry in China were invited to a workshop and 15 people participated in amending the draft CLDs. These 15 people were separated in 5 different groups based on two rules to make sure all the people in one group could share different experiences and options. People were allocated so that in each group:

1. No two people had the same occupation;
2. No two people worked in the same company;

In the 5 groups, different CLDs were provided: 2 represented the bottom and upper half of Fig 3 (a), and 3 further ones had a different focus. There were 2 facilitators allocated to each group. The main role of facilitators was to make sure the discussion keeps going on within the group and that each participant engages equally. In other words, the facilitators were responsible for procedure and process. They were process coordinators, knowledge elicitors and system dynamics educators at the same time [12]. To be effective facilitators, several rules had to be followed, as listed in Table 1. The attitude is the first critical characteristic required. The right attitude could help the discussion going on smoothly and productively. Facilitators should be helping, neural, enquiring, curious, integrity and authentic. The facilitators should not teach but foster reflection and learning in a team by discouraging defensive communication. Although right attitude is critical, certain skills are also required, e.g. process structuring, conflict handling and communication skills. Knowledge of system dynamics and model-building skills are the pre-required for an effective facilitator. Furthermore, the knowledge of green buildings is also required in this participatory modelling. All 5 groups were allocated to different CLDs in the first round and then swapped in the second round. Each participatory modelling round took about 30 minutes. After collecting all the feedback through participatory model refinement, the second version of the CLD was produced as shown in Fig 3 (b), where pink color represents the changes.

Table 1 Rules for facilitators to follow during participatory modelling [13]

Facilitators	Facilitating Attitude	Facilitating Skills
✓ 10 people in total ✓ 2 people in each group	✓ Helping ✓ Neutral (not getting involved in the content of the discussion) ✓ Enquiring/ Curious (asking instead of providing) ✓ Showing integrity & being authentic	✓ Knowledge of system dynamics and model-building skills ✓ Process structuring skills ✓ Conflict handling skills ✓ Communication skills

3 Results

The results are shown in Fig 3, where (a) represents the CLD developed initially and (b) represents the amended CLD after participatory modelling. The CLDs could be understood in this manner: the top part describes the causal links in the design process and the bottom part describes the operational part. There are 5 causal loops in the CLD developed initially, four balancing loops and one reinforcing loop. The reinforcing loop means that all the factors within the loop will keep on increasing with time, in the meanwhile, balancing loops mean the all the factors will reach a balancing point with time. For example, in the top balancing loop, with the increase of building performance gap, facility manager will tend to seek advice from consultant, thus the mismatch between initial design concept and operational strategy would reduce, which will make operational strategy more reliable, actual building performance further increase, and finally reduce the building performance gap. Over time, the building performance gap will not be enhanced but balanced.
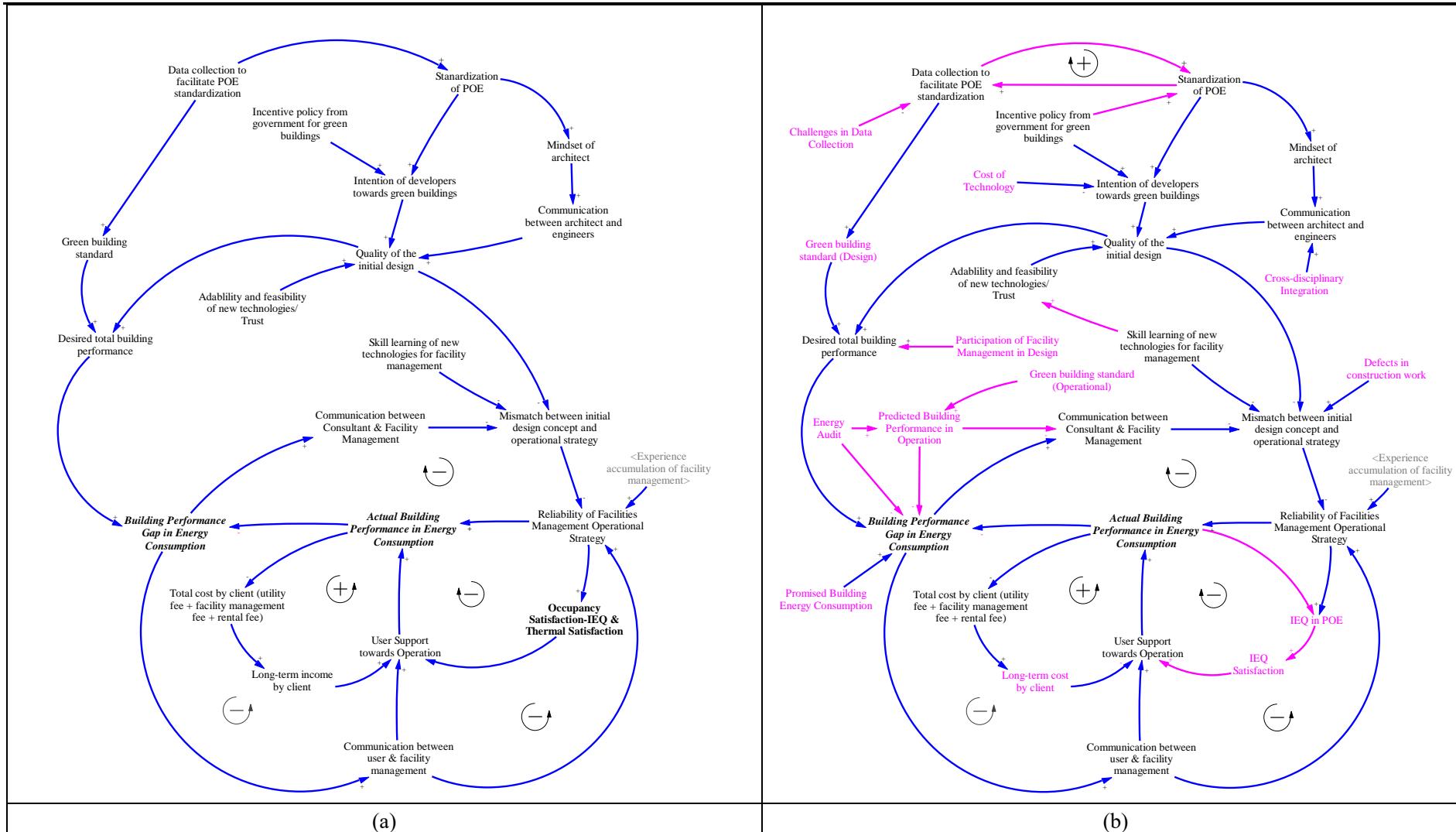
Fig 3 Causal Loop Diagrams: (a) CLD developed initially; (b) amended CLD after participatory modelling

During the workshop, two major discussions happened, one is about the definition of building performance gap and the other is post-occupancy evaluation (POE). Stakeholders agreed that in reality the building performance was not the difference between actual building performance and desired building performance, but instead the difference between the data from energy audit and predicted building performance in operation, which was affected by green building standard (operational). However, the desired building performance and predicted building performance in operation was not directly or indirectly linked, and stakeholders mentioned that these two performances followed two different green building standard, the design standard and operational standard. A facility manager mentioned that there were lots of challenges in data collection, especially the cost, which were the main barriers to data collection. Stakeholders agreed that more data collected definitely could facilitate the POE standardization, also the POE standardization would enhance the process of data collection. Thus a new reinforcing loop was defined.

4 Discussions

4.1 Factors Affecting the Real Building Performance

It is shown clearly in Fig 4 that there are two direct and several indirect factors affecting the real building performance. The two direct affecting factors are the reliability of facility management operational strategy and the user support towards operation. To make the facility management operational strategy more reliable, more communications between user and facility management should be carried out; facility management should have enough experiences and the mismatch between initial design concept and operational strategy should be minimized as much as possible. In order to gain user's support, cost reduction, effective communication and good indoor environmental quality (IEQ) could all help to do so.
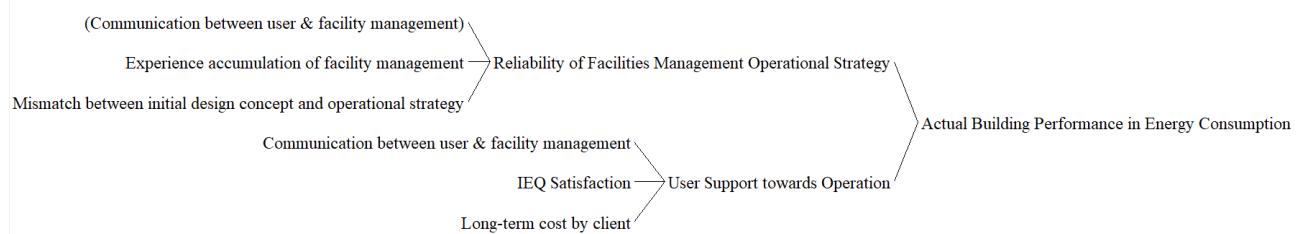

Fig 4 Causal tree for actual building performance in energy consumption

4.2 Factors Affecting the Building Performance Gap

Building performance gap is always found in real buildings and the factors affecting it is clearly shown in Fig 5, where there are five direct and several indirect factors. The five direct factors are actual building performance in energy consumption, desired total building performance, energy audit, predicted building performance in operation and promised building energy consumption. Generally actual building performance is lower than the design building performance, thus, better actual building performance would narrow the performance gap. Energy audit is used to check the real performance and provide suggestions to improve building performance, thus it would help to narrow the performance gap as well. In China, there are two green building standards, design and operational standards, which setting the rules for design team and facility management to follow respectively. In this paper, the desired total building performance is affected by the green building standard (design), while the predicted building performance in operation is affected by the green building standard (operational). Both of the two performances could reduce the performance gap. Finally

promised building energy consumption by developers represents the goal of the project, which would make the performance gap decreased.
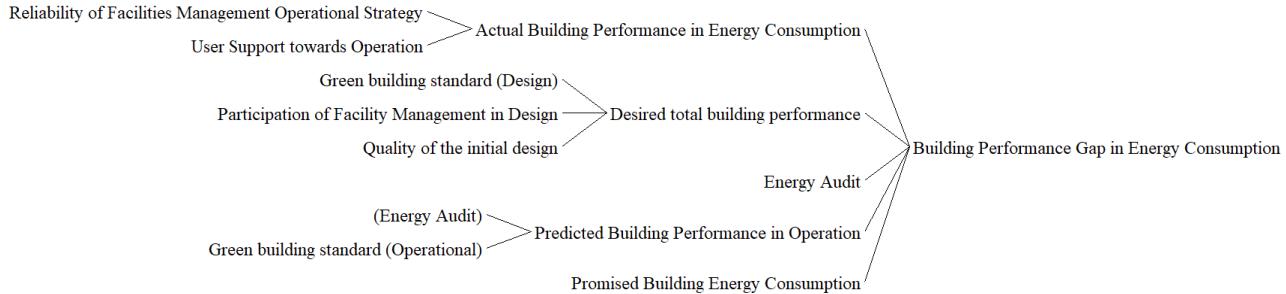

Fig 5 Causal tree for building performance gap in energy consumption

4 Conclusions

This study is the first attempt to apply participatory system dynamics to describe supply chain of the building sector in China. Gaps were found to exist along in the supply chain, especially between stages, and effective communication between stakeholders along the supply chain could help to reduce them. Integrated building design is a good approach to increase the quality of design. In reality, integrated design should be executed throughout the whole process and the facility management team should be provided with an opportunity to share their options in the process. In the future, more simulation results will be produced and presented to public.

Acknowledgements

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