Chapter 85
Construction Schedule Risk Analysis Based on Complex System Theory: Methodology and Empirical Study

Xiaoxiao Xu, Jiayuan Wang, Wenke Huang, Huanyu Wu and Yaning Li

Abstract With the development of China's society and economy, a large number of construction projects are being actively carried out. Project schedule, as one of the major concerns in construction projects, is always affected by high uncertainties and risks brought by the substantial amount of human and nonhuman factors. Therefore, more prominence should be given to proposing effective measures to minimize the losses caused by schedule risks. Although a certain progress has been made from the previous studies, the lack of dynamics and uncertainty analysis lead to results different from reality. This study aims to propose a novel model for analyzing construction project schedule risk. On the basis of complex systems theory, this paper builds a system dynamics model, and encapsulates the system dynamics model into discrete event simulation to form "work module" which can be combined according to the requirements of different projects, Monte Carlo simulation is also employed to analyze the uncertainty of risks. In addition, a WeChat platform is established for collecting schedule risk data. Finally, the present model is validated by a case study after the structure test and behaviors test. The results showcase that: (1) System dynamics can effectively deal with the complex problems of project schedule from the perspective of system, which includes rework, quality problems, the allocation of resource, productivity, decision-making delays, schedule pressure, etc. (2) It greatly improves the applicability of the model to combine system dynamics and discrete event simulation together. (3) Monte Carlo simulation enables the model to obtain the distribution of real-time planned duration in the process of construction, and to be suitable for managers with different risk attitudes and risk-bearing capacity to make decisions.

Keywords System dynamics · Discrete event simulation · Monte carlo simulation · WeChat

X. Xu · J. Wang (✉) · W. Huang · H. Wu · Y. Li
School of Civil Engineering, Shenzhen University, Shenzhen, China
e-mail: wangjy08@qq.com

Y. Wu et al. (eds.), *Proceedings of the 20th International Symposium on Advancement of Construction Management and Real Estate*,
DOI 10.1007/978-981-10-0855-9_85

85.1 Introduction

Nowadays, with the prosperous of China's economy, all kinds of projects are being actively carried out. As one of the pillar industries of the national economy, the construction industry is also booming. Construction is an integrated, systematic and complex social activity. The complexity of a construction project is contributed by the substantial amount of human and nonhuman factors involved in the project. The interaction between factors leads to high uncertainties and risks [1]. Project schedule, as one of the major concerns in construction project management, could be significantly affected by the uncertainties and risks. Current practice of construction risk management relies heavily on experts' experience. However, an individual's beliefs, attitudes, judgments, and feelings may affect his risk perception. Also, professionals can hardly conduct an extensive risk analysis in the early stage due to the uniqueness of every project.

Being aware of the aforementioned situation, this paper aims to propose a novel conceptual model for construction schedule risks analysis by means of complexity science and to provide insights for its utilization for risks prevention and control.

85.2 Methodology and Data

85.2.1 Model Summary

System dynamics, originated by Forrester in the 1960s, is a science which focuses on the structure of complex systems and the relationship between function and dynamic behavior based on feedback control theory and computer simulation technology. System dynamics has been used in a wide variety of applications, such as economic development, military system, energy and resources, urban planning and ecological environment.

Discrete event simulation has great advantages and application prospects in the design and analysis of the dynamic, complex and interactive construction system [2], which is regarded as an effective tool in the quantitative analysis of the events in the whole building facilities life [3]. Discrete event simulation mainly focuses on that the state variables are discrete changed and the system simulation process is driven by discrete event [4].

Monte Carlo simulation is an effective tool for risk analysis. Considering the threats and opportunities and selecting the probability of occurrence of different variables are two important characteristics of Monte Carlo simulation [5]. Monte Carlo simulation may become increasingly important statistical tools to help risk assessors accessing a risk of uncertainty [6].

85.2.2 Study Area

China Union Technology Building, located on the C17-2 ground in Dayang stone village of the High-tech zone, is being built by CMCU. The expected period of construction is nearly 3 years from 1 December 2013 to 31 December 2016. This building is an office and ancillary facility. It has 26 floors, of which 5 floors underground and 21 floors on the ground. The project uses the frame-core wall structure form and its design working life is 50 years. In addition, the construction design grade of this project is grade 1 and the total number of indoor parking spaces in this building is 480.

85.3 Complex System Modeling

85.3.1 Construction of System Dynamics Model

Based on the research of Nguyen and Ogunlana [7], Lee et al. [8] and Wang [9], this paper divides system dynamics model into construction process subsystem, resource subsystem, schedule target subsystem and project performance subsystem. Subsystems are connected to and associated with each other. The system dynamics model is shown in Fig. 85.1.

For example, if quality problems have been found, rework and schedule delay may happen. Therefore, project performance subsystem is interrelated with

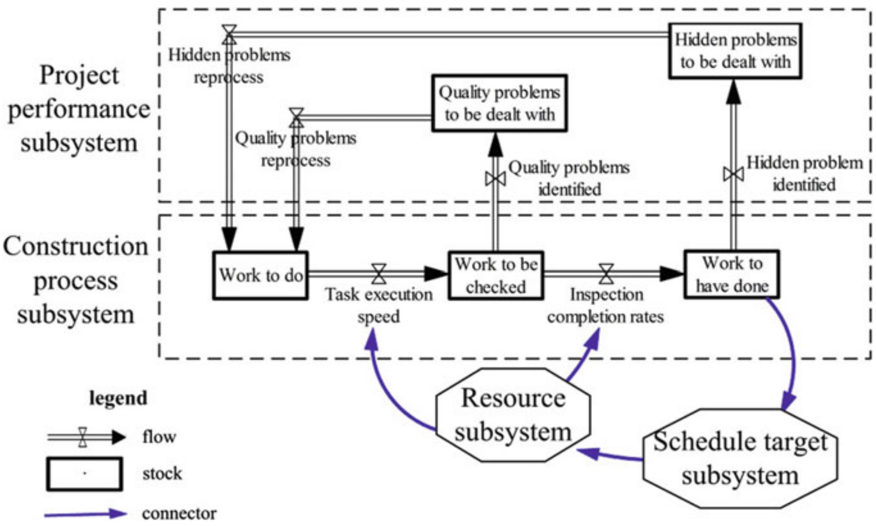

Fig. 85.1 System dynamics model

schedule target subsystem. On the other hand, project performance subsystem is also interrelated with construction process subsystem as getting work done faster may increase the likelihood of the occurrence of project quality problems.

85.3.2 Construction of Discrete Event Simulation Model

A major feature of the discrete event simulation is modeling from micro-level. A project work unit is built by discrete event simulation. In order to achieve the target, the property of a basic unit should be defined. For example, earthwork construction, drilling, geothermal pipe channel construction and infrastructure construction are set as work unit, logical relationships between the work units (including preceding activity, following activity and bonding relation), duration, start time, working hour requirement and resource requirement should be defined. In discrete simulation process, the start time and duration of work unit will change with the impact of schedule risk, which provides data support for system dynamics model.

85.3.3 Building the Interactive Board Comprised of System Dynamics, Discrete Event Simulation and Monte Carlo Simulation

A model that could only be applicable to a particular project can hardly be considered as successful. One of the objectives of this research is to build a model with a high level of university. To achieve this, a completely new concept is adopted in this study: packaging a system dynamics model into a module of the discrete event simulation (namely a job of the model) to constitute a concrete "work module". Different work modules could be combined in order to get a schedule risk systematic analysis model which suits the requirement and characteristics of different construction projects. The process is shown in Fig. 85.2.

85.3.4 Building a WeChat Platform to Get Schedule Risk Information

People may not always take a computer at site, but they will always have a cell phone on hand. It is more convenient for a person to collect real-time data by cell phone than by computer [10]. In order to obtain schedule risk information effectively, a WeChat platform, as shown in Fig. 85.3, which can be accessed by construction project stakeholders is established. Any project stakeholder with a

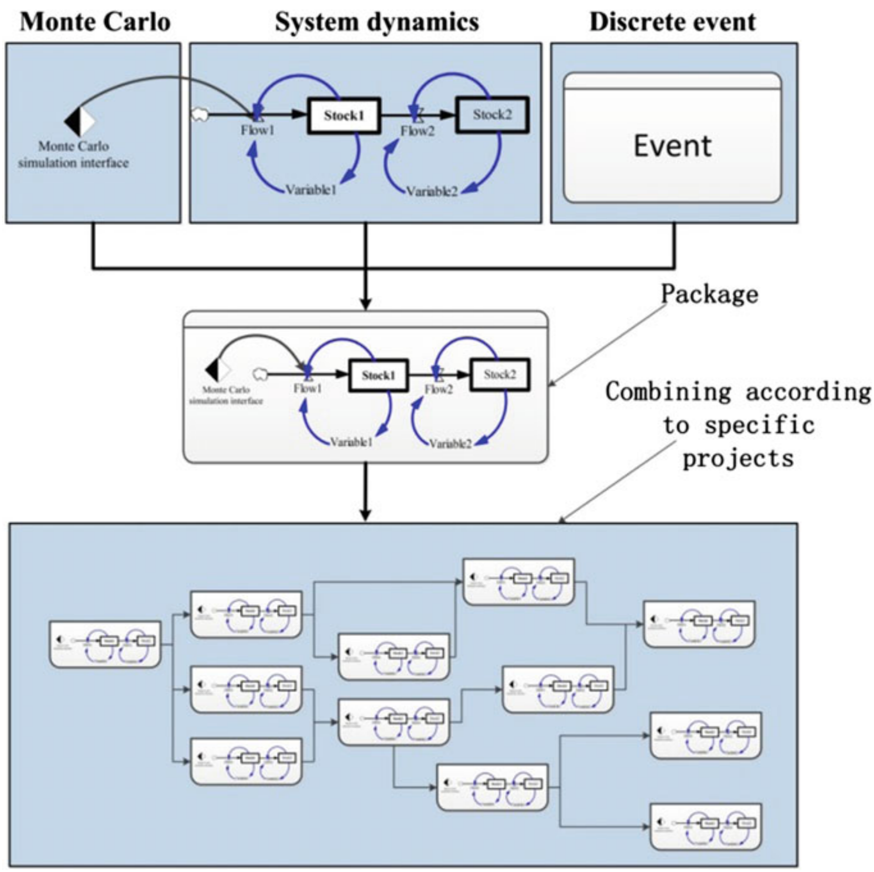

Fig. 85.2 The schematic diagram of model combination

WeChat account can enter the platform and input the construction information (including the schedule risk data in the process of construction). These data will be sent into database and form massive data. By data mining, the probability distribution of each schedule risk can be obtained. The probability distribution will then be inputted into the system model for simulation. Through such processes, users are allowed to forecast the impact from risks to their project more accurately.

85.3.5 Model Test

To test the validity of the model, model structure test and model behavior test are adopted.

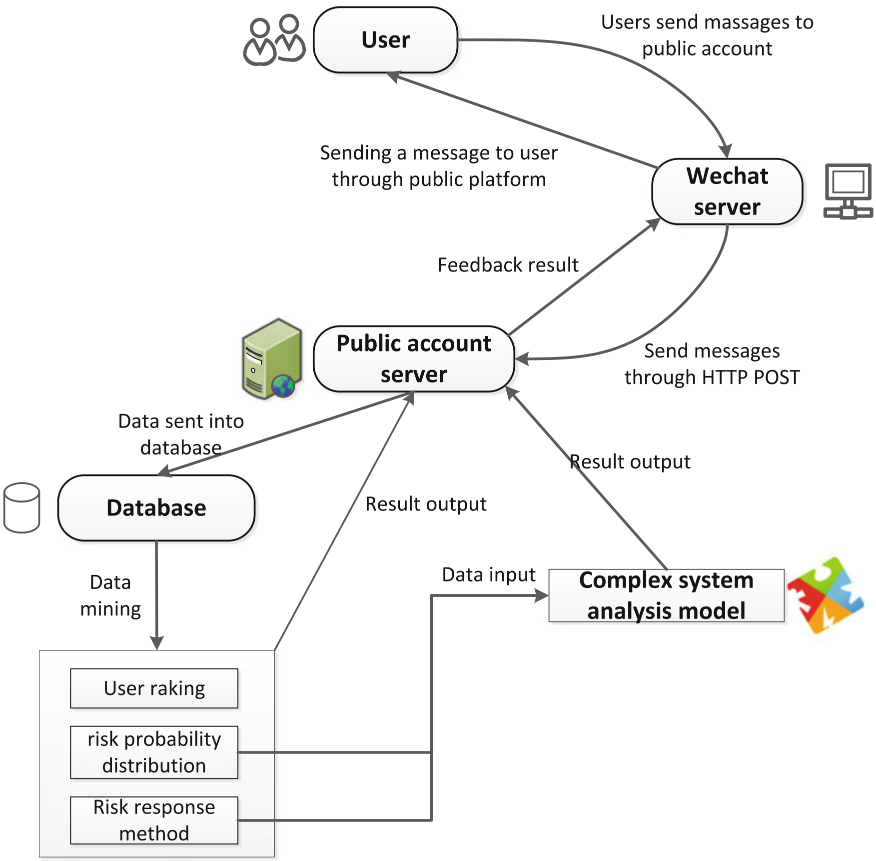

Fig. 85.3 The overall framework of WeChat platform

Model Structure Test

Model structure test includes direct structure tests and structure-oriented behavior tests [11, 12]. Direct structure test contains structure confirmation test, parameter confirmation test, boundary adequacy test and dimensional consistency test [11, 13]. Through a symposium of experts, system dynamics model is properly modified and in line with direct structure test. Structure-oriented behavior rest involves extreme-condition test, behavior sensitivity test and integral error test. The purpose of extreme-condition test is to test whether system dynamics model is consistent with common sense under extreme condition. We set all the variables associated with schedule risks to be 0 and find the output conform to actual situation, which prove the model meets the requirement of extreme-condition test. The role of behavior sensitivity test is to identify sensitive parameters in system dynamics model. By sensitive analysis, we find all sensitivity parameters are in permitted range, which indicate the model in line with the requirement of behavior sensitive test. Integral error test is aiming at determining whether model is sensitive to difference step and integral mode. By the way of changing difference step and integral mode, we find the output change a little, which demonstrate the model meets the requirement of integral error test.

Model Behavior Test

Historical data comparison analysis is adopted for model behavior test. The common practice is to check whether the simulation results are in line with the corresponding historical data [14]. Considering that it is not practical to demonstrate all the output variables due to the lack of historical data, we choose real-time planned schedule as indicators. The model simulated variable value is compared to its historical data. The average error of each variable is 0.0045 %, and the variable whose relative error is less than 5 % accounts for 100 %, which indicates the validity of our model in agreement with the requirement of model behavior test [15].

85.4 Case Study

One of the most important indicators to measure project delay is the real-time planned schedule. The longer the project is postponed, the more influential the schedule risk is. By simulation, we can attain the dynamic changes of schedule risk, as shown in Fig. 85.4. The horizontal axis in Fig. 85.4 indicates "Time" and the vertical axis represents "real-time project schedule". Curve 1 means the planned schedule, which means the real-time project schedule equals the planned schedule without risk. Once risks occur (as risk 1 and risk 2 in Fig. 85.4), the real-time project schedule increases. Afterwards, the real-time planned schedule will decline

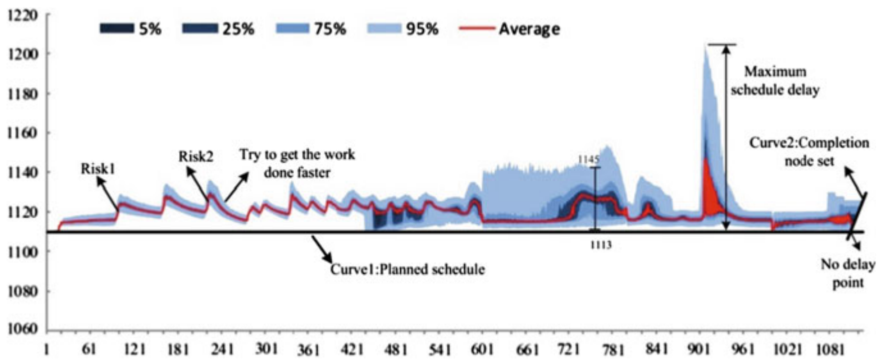

Fig. 85.4 Risks dynamic change

and constantly approach curve 1. Due to the uncertainty of risk, system model will simulate hundreds or even thousands of times and will generate thousands curves. By probability statistics of the value on the curves, we can get the distribution of real-time planned schedule in everyday under the action of risks. Take the 761th day for example, the real-time planned schedule has 95 % chance between 1113 and 1145 and has 75 % chance between 1120 and 1130. The difference value between the ordinate of each curve and curve1 indicate schedule delay. We can see from Fig. 85.4 that the risk which impacts the most occurs at the 902th day and it causes the real-time planned schedule reach to 1200 days. The end point of each curve constitute curve 2 (completion node set) which is a straight line with a slope of 1 (because only when the time equals to real-time planned schedule will the project finish). The curve, the end point of which is (1110, 1110), indicates the schedule is not postponed. Apart from this, all the curves are postponed. Project manager can import the identified risks into the model in different times according to their needs, and they can get: (1)the impact of risks on the project at the same time; (2)the impact of different risk on the project at the same time; (3)the impact of different combinations of risk on the project. Due to the fact that the output can express the uncertainty of risks, the decision maker with different risk attitude can make different response program according to the output.

Further data mining can be conducted for the impact of schedule risk according to output data from risk dynamic change chart. As shown in Fig. 85.5, the horizontal axis represents the risk occurrence time and the vertical axis represents the average of real-time planned schedule which is the ordinate of red curve in Fig. 85.4. Each “bubble” in Fig. 85.5 represents a risk, the radius of which indicates the schedule fluctuation. The bigger the radius is, the more significant the fluctuation is. The following information can be obtained from Fig. 85.5: (1)average schedule delay, the ordinate of each bubble’s center indicates the average schedule delay under a certain risk; (2)the impact of the same risk happens at different times, for example, rework occurs at the 110th day, the 171th day and the 589th day

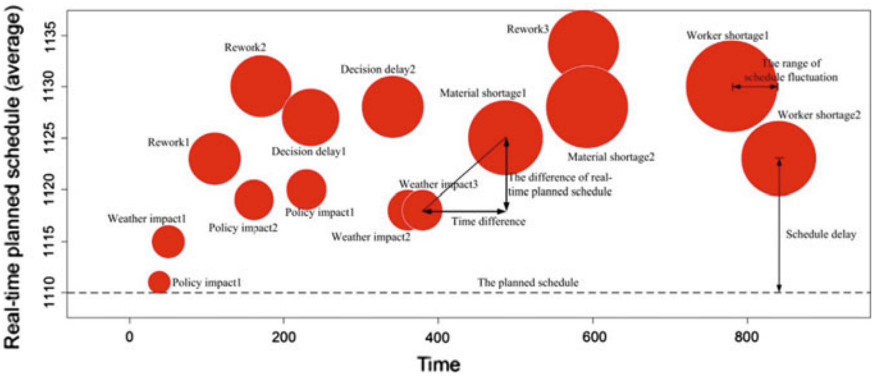

Fig. 85.5 Risk measure

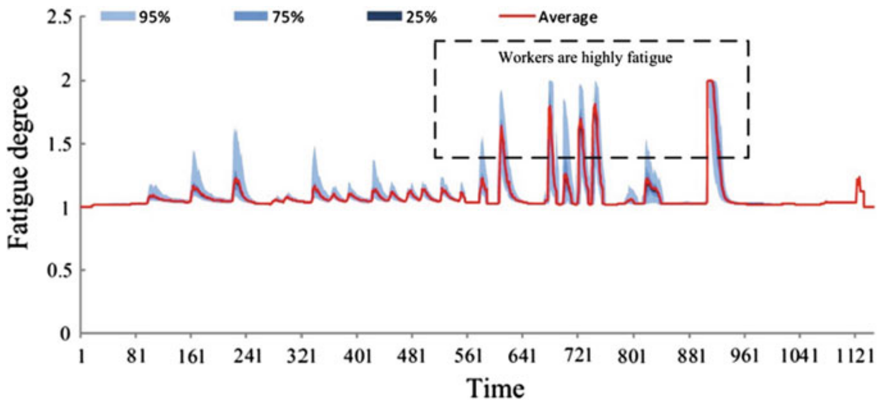

Fig. 85.6 Fatigue degrees in the process of construction

respectively (Fig. 85.5 only intercepts a part of the risks). By comparing the ordinates and radius of the three "bubbles", the impact of risk occurring at different time can be obtained (rework1 < rework2 < rework3); (3)The comparison of the effects of any two schedule risk. Any two schedule risk (e.g. weather impact3 and material shortage2) in Fig. 85.5 can constitute a right triangle. The length of horizontal angle side of right triangle represents time difference, namely the time difference between two risks. In Fig. 85.5, weather impact3 happens 108 days earlier than material shortage2. It indicates that two risks happen at the same time when the time difference is zero. The length of vertical angle side of right triangle represents the difference of real-time planned schedule, for example, the schedule delay caused by material shortage2 is 8 days more than the schedule delay caused by weather impact3.

In addition to the result of project schedule, we can also attain the change of other variables over time, such as fatigue degree, as shown in Fig. 85.6. Worker's fatigue degree is between 1 and 2. 1 shows fatigue does not exist, while 2 represents worker has extreme fatigue. Overtime is the main reason for fatigue. We can see from Fig. 85.6 that fatigue exist slight fluctuations in the first 500 days. From the 500th day to 1000th day, workers repeatedly experience extreme fatigue. In the case of extreme fatigue, construction workers most likely to make a mistake which will lead to schedule delay to a certain extent and create a vicious cycle.

85.5 Conclusion

With the help of complex system theory, this study succeeds in proposing a novel conceptual model and demonstrating its application for construction project schedule risk analysis. However, there are still shortcomings in the process of the analysis concerning the influence of construction project schedule risks. For example, interactions between environment, safety, cost and schedule have not been considered in the analysis. Similarly, interactions between risks have not been taken into account. It is the writers' opinion that future studies can be developed in the following directions: (1) Combining the model in this study with BIM. Each task can be connected with architectural models in BIM model library making it possible to conduct system simulation and 3D virtual building simultaneously. (2) Considering cost, schedule, quality, environment and safety, and building a comprehensive system analysis model. (3) Collecting real-time data in the construction process more effectively with the help of the Internet of things.

Acknowledgements We thank National Natural Science Foundation of China (No. 71272088) for their financial support of this research.

References

1. Choudhry RM, Aslam MA, Hinze JW, Arain FM (2014) Cost and schedule risk analysis of bridge construction in Pakistan: establishing risk guidelines. J Constr Eng Manage 140(7)
2. Lu M (2003) Simplified discrete-event simulation approach for construction simulation. J Constr Eng Manage 129(5):537–546
3. Martinez JC (2009) Methodology for conducting discrete-event simulation studies in construction engineering and management. J Constr Eng Manage 136(1):3–16
4. Law AM, Kelton WD, Kelton WD (1991) Simulation modeling and analysis, vol 2. McGraw-Hill, New York
5. Rezaie K, Amalnik MS, Gereie A, Ostadi B, Shakhseniaee M (2007) Using extended monte carlo simulation method for the improvement of risk management: consideration of relationships between uncertainties. Appl Math Comput 190(2):1492–1501
6. Hayse JW (2000). Using monte carlo analysis in ecological risk assessments. Argonne National Laboratory, USA, Oct 27
7. Nguyen LD, Ogunlana SO (2005) Modeling the dynamics of an infrastructure project. Comput Aided Civil Infrastruct Eng 20(4):265–279
8. Lee S, Han S, Peña-Mora F (2009) Integrating construction operation and context in large-scale construction using hybrid computer simulation. J Comput Civil Eng 23(2):75–83
9. Wang Y (2011) The research on system dynamics simulation-based tome control methodology for complex construction project. Tongji university, China
10. Lee H, Park H, Kim J (2013) Why do people share their context information on social network services? A qualitative study and an experimental study on users' behavior of balancing perceived benefit and risk. Int J Human–Comput Stud 71(9):862–877
11. Barlas Y (1996) Formal aspects of model validity and validation in system dynamics. Syst Dyn Rev 12(3):183–210
12. Barlas Y, Kanar K (2000) Structure-oriented behavior tests in model validation. In 18th international conference of the system dynamics society, Bergen, Norway, pp 33–34
13. Lee S, Peña-Mora F (2007) Understanding and managing iterative error and change cycles in construction. Syst Dyn Rev 23(1):35–60
14. Li Z, Shen GQ, Alshawi M (2014) Measuring the impact of prefabrication on construction waste reduction: an empirical study in China. Resour Conserv Recycl 91:27–39
15. Maddala GS (1986) Limited-dependent and qualitative variables in econometrics. Cambridge university press, USA