# Dynamic Project Management: An Application of System Dynamics in Construction Engineering and Management

**Sangwon Han, SangHyun Lee and Moonseo Park**

**Abstract** Computer simulation is one of the most widely utilized tools for operational research in construction engineering and management. Although discrete event simulation (DES) has been extensively utilized in construction, system dynamics (SD) has received relatively little attention despite its great potential to address dynamic complexity in construction projects, which are inherently complex, dynamic and involve multiple feedback processes and non-linear relationships. This chapter introduces dynamic project management (DPM), an SD-based new construction project modeling approach, which has been successfully applied to deal with dynamic complexities in diverse infrastructure and building projects. Particularly, this chapter introduces three major theoretical foundations of DPM: a holistic approach, a system structure-oriented approach, and the incorporation of control time delays. This chapter is expected to serve as a useful guideline for the application of SD in construction and to contribute to expanding the current body of knowledge in construction simulation.

**Keywords** Simulation · Discrete event simulation · System dynamics · Control theory

---

S. Han (✉)
Department of Architectural Engineering, University of Seoul, Seoul, Korea
e-mail: swhan@uos.ac.kr

S. Lee
Department of Civil and Environmental Engineering, University of Michigan,
Ann Arbor, MI, US
e-mail: shdpm@umich.edu

M. Park
Department of Architecture, Seoul National University, Seoul, Korea
e-mail: mspark@snu.ac.kr

H. Xu and X. Wang (eds.), *Optimization and Control Methods in Industrial Engineering and Construction*, Intelligent Systems, Control and Automation: Science and Engineering 72,
DOI: 10.1007/978-94-017-8044-5_13,

# 1 Introduction

Computer simulation is the process of designing a mathematical-logical model of a real system and experimenting with this model on a computer [1]. It enables testing without disruption of ongoing operations and committing physical resources, testing hypotheses for feasibility study, compressing or expanding time for closer observation, gaining insight about complex systems, identifying system bottlenecks and providing answers for “what if” scenarios [2]. The availability of special-purpose simulation languages, massive computational capabilities at a decreasing cost per operation, and advances in simulation methodologies have made simulation one of the most widely used and accepted tools in operations research [3].

Computer simulation has also been extensively utilized in construction over the past decades. While discrete event simulation (DES) has predominantly been used in the history of construction simulation development, system dynamics (SD) has received relative little attention despite its great potential to address dynamic complexity in construction. Therefore, research has recently focused on applying SD in the area of construction engineering and management. In order to explore the applicability of SD in construction engineering and management, this chapter introduces dynamic project management (DPM), an SD-based new construction project modeling approach. The findings from this chapter are anticipated to expand the current body of knowledge in construction simulation and provide valuable lessons to construction researchers and practitioners seeking to develop SD models.

This chapter first examines differences between discrete and continuous simulation and then explains the dominance of DES in the history of construction simulation development. Next, the capabilities of SD are explored and the applicability of control theory and construction management examined. Lastly, three major theoretical foundations of DPM are provided and conclusions are drawn focusing on its opportunities, benefits, and further improvement in the area of construction engineering and management.

# 2 Discrete Versus Continuous Simulation

Simulation models can be largely classified as either discrete or continuous based on the timing of state change. Few systems in practice are wholly discrete or continuous, but since one type of change predominates for most systems, it is usually possible to classify a given system as either discrete or continuous [4]. It is possible to model the same system with DES or a continuous simulation CS; [1] and the choice between these options is a function of the characteristics of the system and the objective of the simulation [3].

## 2.1 Discrete Event Simulation (DES)

DES is the modeling of systems in which the state variables change only at a discrete set of points in time [3]. The aim of a DES model is to reproduce system activities that the entities engage in and thereby learn something about the behavior and performance potential of the system [1]. That is, an artificial history of the system is generated based on the model assumptions, and observations are collected to be analyzed and to estimate the true system performance measures [3].

A typical example showing the concept of DES is a bank teller model that mimics a teller at a bank processing customers' transactions. The central purposes of this type of model are to forecast (a) the average time a customer spends at the bank, and (b) the proportion of the time that the teller is idle. In this model, each customer arrives at the bank at a random time (i.e., event time). On arrival, if the teller is busy (i.e., serving a customer who arrived at the bank earlier), the customer joins a queue and waits until the teller is idle (i.e., finished serving the previous customer). Then, the customer is served for an uncertain duration of time and finally leaves the bank.

In this model, the system states (e.g., status of the teller and number of waiting customers) are changed only when a customer arrives at the bank or departs the bank (i.e., event time). For example, on the arrival of a customer, if the teller is idle, the status of the teller is changed to 'busy' and the teller starts serving the customer. Otherwise, the customer waits in the queue and the number of waiting customers is increased by one. On the departure of a customer, if the queue is empty, the status of the teller is changed to 'idle'. Otherwise, the teller continues serving the next customer and the number of waiting customer is decreased by one. Since DES assumes the system states remain constant between event times, a complete portrayal of the system state can be obtained by advancing simulation time from one event to the next [1].

## 2.2 Continuous Simulation (CS)

In CS, changes in the state of a system occur continuously over time [3]. As discussed above, DES focuses on a distinct individual entity (e.g., customer) in a system and keeps track of the time taken for each entity (e.g., waiting time or service time of each customer). On the other hand, CS regards an entity as a continuous quantity (e.g., water) flowing through a system and focuses on the rate of change in the entity during the specified time unit [5]. Thus, while system state variables are determined by the sequence and timing of random events in DES, CS is usually constructed by defining mathematical equations for a set of the system state variables. Differential equations are frequently used in describing the system state variables in CS due to their effectiveness in representing the rate of change over time [1]. For example, the current state of a variable ($S(t_2)$) can be derived from its previous state ($S(t_1)$) and the rate of change over the specified time duration as shown in Eq. (1).

$$S(t_2) = S(t_1) + \int_{t1}^{t2} \left(\frac{dS}{dt}\right) dt \tag{1}$$

As expressed in Eq. (1), the system state variables are updated at finely-sliced time steps of equal duration in CS but at random event times in DES. For example, when modeling a situation where 1.25 h is taken to produce a unit, DES updates the cumulative number of production by '*one unit after* 1.25 h '(i.e., entity-based system update) while CS updates by '0.8 *units after* 1 h' if the time step is 1 h (i.e., time-based system update). Accordingly, in this case, DES assumes that there has been no progress during the first one hour while CS assumes that 0.8 units of progress have been made. From the point of view of '*production planning*', DES estimation looks more realistic and valid, whereas from the viewpoint of '*progress monitoring*', CS calculation can be more informative than DES estimation. However, it should be noted that both DES and CS assume an absence of any progress during the first half hour (when the time step is 1 h). For these reasons, when more accurate simulation results are required, DES tends to further divide an activity (e.g., production) into several sub-activities (e.g., cutting, assembling, bolting, painting and packing) while CS tends to adopt a smaller time step (e.g., 0.5 or 0.25 h).

These differences imply that DES is more efficient for point estimation (e.g., calculation of exact timing of unit production) but CS is more effective for pattern estimation (e.g., projection of progress behavior over time). Of course, it is possible for CS to detect more accurate time positions (e.g., 1.25 h) by decreasing the time step (e.g., 0.25 h). However, achieving greater accuracy in CS by using smaller time steps incurs a cost in terms of increased computational time and effort [6].

## 3 Construction Simulation

Construction simulation is the science of developing and experimenting with computer-based representations of construction systems to understand their underlying behavior [7]. Simulation has been widely applied as an effective planning and performance improvement tool in the construction management area by virtue of its advanced capabilities to analyze complexity and uncertainty [8].

Examining the history of construction simulation, it is clear that the prevalent approach for construction simulation has traditionally been DES [7, 9, 10]. The dominance of DES in the construction simulation area is primarily attributed to its advanced capabilities providing operational details that are not readily provided by network-based approaches (e.g., CPM/PERT) [11]. Current construction management approaches including CPM/PERT are conceptually rooted in the idea of decomposition [12] where it is generally hypothesized that the complexity of a project can be reduced by subdividing the project into manageable smaller activities [13]. Consequently, the general direction of these approaches is in deconstructing further into even smaller fragments of a construction project and searching for explanations at the lowest possible level [14].

These decomposition-based approaches can provide detailed information regarding 'what to build' at an activity level by subdividing a project (it is not unusual for a modern construction project to include thousands of activities), but are limited in representing 'how to build' at an operational level. For this matter, DES is an effective complementary tool that can deal with operational details (e.g., resource status). For example, the CPM/PERT generally represents earthmoving as a single activity, whereas DES zooms into its internal operational logistics and analyzes complex interactions between work tasks (e.g., load, haul, dump) and resource assignment (e.g., pushers, scrapers).

As such, utilization of DES enables management of several complex problems including bottle-neck analysis, sensitivity analysis, resource balance analysis, productivity improvement, process optimization, and so forth [15]. Because of the advanced problem solving capabilities of DES under the popularity of decomposition-based approaches, the construction management discipline has encouraged a narrow, partial view of a project, concentrating on the detailed planning of individual discrete activities and operational details [16–19].

However, due to its narrow focus and partial view, DES can sometimes provide unrealistic estimations because operational performance is significantly affected by the project contexts (e.g., schedule urgency) that are determined by other concurrent operations [9]. Thus, there is a strong need to apply simulation to high-level strategic decision making beyond construction operations [15]. Based on the analysis of 3,500 projects, [18] reported that lack of strategic analysis is a major reason for the failure of many projects. Considering the complex interrelationships between processes, subcontractors, resources, etc., in a construction project, the use of simulation for high-level strategic decision making requires a holistic approach because appropriate policies cannot be made without a complete understanding of the whole project structure [20]. For this reason, it is difficult to use DES models (based on reductionism) for high-level decision making [21]. To address this deficiency, several researchers have proposed SD as a complementary tool to DES in the strategic decision making process.

## 4 System Dynamics (SD)

SD is a methodology used to understand how systems change over time. The idea of SD originally stems from a servomechanism for automatic machine control. The concept of the servomechanism evolved during and after World War II and has been used in many engineering occasions [22]. The servomechanism is an acting machine to control the operation of a larger machine by virtue of feedback [23] and its entire science has been known as control theory. A good example is a thermostat that receives temperature information and can raise or lower the temperature operating a heater or cooler. Beyond its application to engineering, this concept is fundamental to all life and human endeavor: a person senses that he may fall, corrects his balance, and thereby is able to stand erect; a profitable industry attracts competitors until the profit margin is reduced to equilibrium with other economic forces, and competitors cease to enter the field; the competitive need for a new product leads to research and development expenditure that produces technological change [22]. Though the majority of its application has been to ‘hard’ systems such as a mechanical control system, which provides more controllable environment, it can be also applied to ‘soft’ systems such as a management control system because it is also a fundamentally feedback-driven system [6]. Consequently, significant research efforts have been directed at understanding social systems since the late 1950s. These efforts have proceeded under the term SD, which is an approach to understand the behavior of complex systems over time using computer simulation.

By virtue of feedback structure analysis, SD can provide analytic solutions for complex and non-linear systems [6]. Hence, SD is well suited to dealing with the dynamic complexity in construction projects, which are inherently complex and dynamic, involving multiple feedback processes and non-linear relationships [24]. However, as previously discussed, DES has dominated the history of construction simulation and SD has received relatively little attention in construction despite its great potential. In order to fully explore the applicability and utilize the benefit of construction simulation, SD needs to be further investigated. To address this need, this chapter introduces DPM, which has been successfully applied to diverse infrastructure and building projects [20, 25, 26]. Particularly, this chapter focuses on the theoretical foundation of DPM by applying the original concept of control theory to construction engineering and management, instead of repeating the successful applications of DPM, which have been well reported [20, 25, 26].

## 5 Control Theory and Construction Management

Control theory has played a vital role in the advance of engineering and science [27]. Control theory aims to produce the desired or optimal outcome of the system, and its main mechanism is feedback control. Feedback represents that the output of a system is passed back to its input. In control theory, feedback is used as follows: (1) the output of the system is compared to the desired state, initially set as a reference; (2) control actions are taken to reduce this gap if any; and (3) this process is iterated until the desired state is realized to control the system. Figure 1 illustrates a simplified feedback control. Specifically, there is a plant, the object or system to be controlled, which is a combination of components that act together and perform a certain objective [27]. The plant is working with its reference (i.e., desired state), and its output (i.e., actual state) is monitored through a sensor so that the gap between reference and feedback signals (i.e., error, A in Fig. 1) can be captured. If there is any gap between them, a controller takes some control actions to reduce this gap. In addition, there can be external disturbances, which tend to adversely affect the output of a system [27]. These control actions and disturbances (B in Fig. 1) act as another input for the plant, and the sensor monitors the corresponding output. The feedback process is reiterated toward the goal where the actual state meets the desired state during the entire life

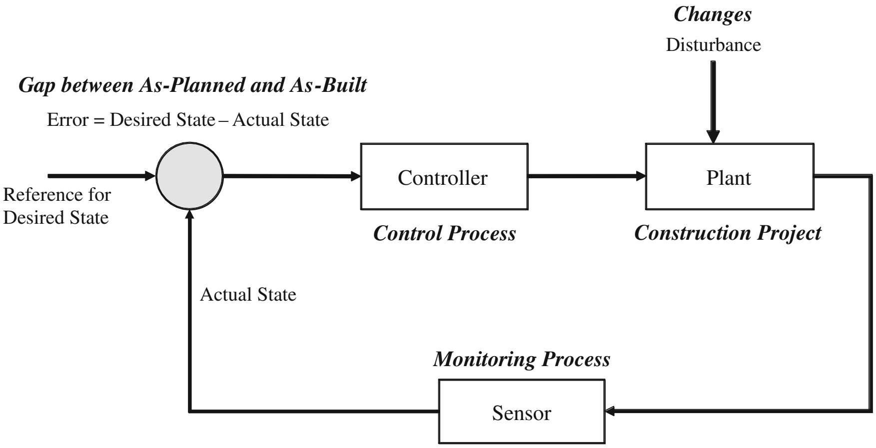

**Fig. 1** Control theory: Feedback control system

cycle of this system. The objective of the feedback control system is to design the system which produces the desired state despite error and disturbance.

Close investigation enables an analogy to be drawn between the feedback control system and project management in construction, as seen in Fig. 1 (the italics in Fig. 1 represent control theory's analogy to project management). For example, the plant in control theory can correspond to a construction project. The project is composed of many components, such as subcontractors, activities, resources, and equipment, which are all linked to each other. The project is implemented to produce its objective, as-planned performance (i.e., the desired state). The output of the project, as-built performance (e.g., the actual state), is monitored through a monitoring process (e.g., quality management process) analogous to the sensor in control theory. If there is any discrepancy between as-planned performance and as-built performance, control actions, analogous to controller in control theory, are taken to reduce this discrepancy. Additionally, there can be changes from outside the project analogous to the external disturbances in the control system, such as the owner's change request or a regulation change, which will disrupt project performance. These control actions and changes act as another input for the project, and the feedback processes will be reiterated during the life cycle of the project until the desired state is met.

The analogy from control theory implies that the dynamics is a major driver that renders the project management difficult, and the feedback can greatly intensify it. In construction, as-built performance is usually different from as-planned performance, so that significant efforts have to be made to reduce this gap. However, sensing as-built performance accurately is not an easy task. For example, the frequent manual collection of as-built performance requires a lot of effort from field crews and, further, is based on their subjective estimation. In addition, the taken control actions are not always appropriate and can even worsen the situation because they may be based on wrong as-built information. Furthermore, the decisions are often made under limited time, budget, and resources. As a result, the gap can be increased, leading to chains of problems. The feedback that aims at stabilizing the project may actually intensify such dynamics.

In dealing with such situations, control theory provides valuable lessons to manage such dynamics. First, construction should be understood and managed as a whole including a sensor and a controller. Traditional management approaches have often focused on the project itself, particularly its operations. However, control theory shows that the project is so dynamic and feedback-driven that it cannot produce the desired state without the deliberate use of the sensor and the controller. Furthermore, construction is usually executed in an open environment and is therefore vulnerable to uncertainties, such as weather and differing site conditions. In addition, there are many change orders in the project, which also make it difficult to achieve the desired state. With respect to these issues, control theory suggests that the well-designed and implemented system with the help of a sensor and controller can stabilize the system despite such disturbance. Thus, there is a strong need for an approach that can take into account not only the project, the sensor, and the controller, but also, and more importantly, their interactions. In this way, the dynamics of the project can be better understood and controlled.

## 6 Theoretical Foundations of Dynamic Project Management (DPM)

Adopting SD as an implementation mechanism, DPM is proposed as a new method to manage dynamic complexities in construction projects. Its underlying philosophy is that construction is a system, with the parts working in coordination, which changes over time. Stemming from this philosophy, DPM focuses on the following characteristics to better understand and manage construction projects as a theoretical foundation: a holistic and a structure-oriented approach, and understanding of prevalent time delays. The following sections will investigate each of these foundations in detail.

### *6.1 Holistic Approach*

As discussed earlier, the design of a construction system including a sensor and a controller is essential to achieve the desired state of construction performance. Thus, a holistic approach that simultaneously considers the project, the sensor, and the controller is one of the core foundations taken by DPM. This assumes that the actual output of a project is different from the desired output so that the sensor and the controller should be deliberately designed as the system core. In this regard, change should be also considered as a natural part of construction. Usually, change is con-

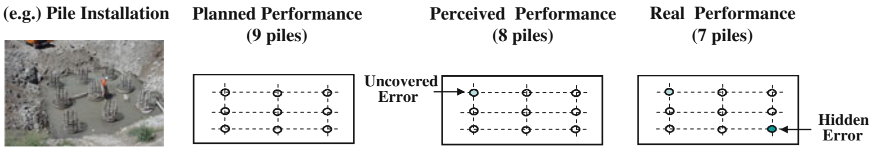

**Fig. 2** Planned, perceived, and real performance at pile installation example

sidered as ‘out of control’ because it often occurs from the outside project. However, an analogy from control theory reveals that the project can be stabilized based on the quality of the feedback control system despite outside disturbances. Designing a project indifferent to change may not be achievable. However, minimizing the impact of change is possible with the help of a well-designed sensor and controller, and this is worthwhile considering the overwhelming negative impact of changes. Thus, the project, sensor, and controller should be designed and implemented in an integrated fashion to cope with the dynamics of project management.

To this end, the use of automatic data capture (ADC) and computer simulation technologies has a great potential; the former for real-time monitoring and the latter for decision making support. For example, real-time performance information obtained from ADC can be input to computer simulation for diverse what-if scenarios of possible corrective actions (e.g., resource allocation strategies). In this way, the project, the sensor, and the controller can be integrated so that the performance gap can be addressed promptly and effectively.

## *6.2 System Structure-Oriented Approach*

An event is the particular happening at a point of the system’s behavior and this dynamic behavior arises from the system structure [6]. System structure is identified as the interactions of two types of feedback: positive (or self-reinforcing) and negative (or self-balancing). A positive loop tends to reinforce or amplify whatever is happening in the system and a negative loop counteracts and opposes change [6]. Understanding the interactions between these feedback processes can greatly contribute to the management of dynamic behavior. It is also very useful to devise corrective actions analyzing their possible consequences.

Suppose we are installing nine piles for foundation, as illustrated in Fig. 2. If performance is measured by the number of completed piles, completing nine piles is the planned performance. However, if we find a pile with strength failure during a quality management process, eight piles are actually completed (i.e., perceived performance) and, thus, the gap between planned and perceived performance is one pile. In this case, managers take corrective actions, usually accompanied by an increase of scope, in an attempt to reduce this gap. For example, we may need to remove the existing erroneous pile and install a new one, which assigns additional scope. This

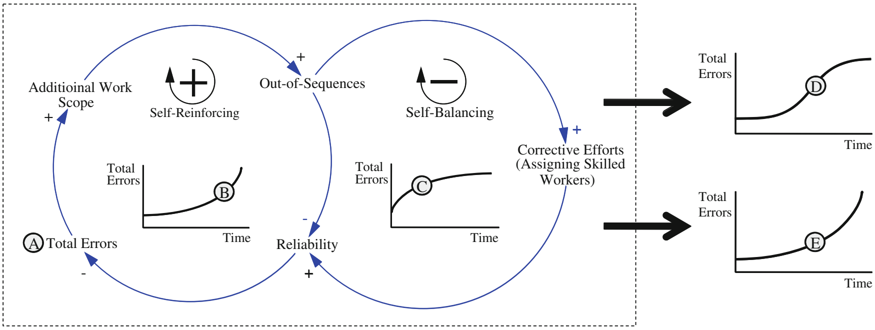

**Fig. 3** Interaction of feedbacks and resultant behavior

scope increase creates feedbacks that result in complex dynamics. As illustrated in Fig. 3, the scope increase caused by errors (i.e., Total Errors, A in Fig. 3) can disrupt a series of intended construction sequences. In this pile installation example, we may need more additional resources such as material, equipment, and man-hours, to remove and install a new pile putting on hold other succeeding activities. Further, if contingent resources are limited, procuring them may generate more issues, such as resource shortage in the succeeding activities. This will deteriorate overall project reliability, the degree to which performed tasks have been done correctly [20], leading to more Total Errors (A in Fig. 3). This will create a self-reinforcing feedback that amplifies out-of-sequence and can generate exponential growth behavior (B in Fig. 3) [6]. On the other hand, if serious out-of-sequence is experienced, a project manager can take corrective actions to rectify it. For example, more skillful workers can be assigned in order not to repeat the same error while increasing production rate. This aims at improving reliability and can reduce error. As such, the degree of out-of-sequence will be alleviated and a self-balancing feedback will be generated, which counteracts out-of-sequence and generates goal seeking behavior (C in Fig. 3) [6]. Finally, the interaction of these two different feedbacks generates complex dynamics. For example, based on the effect of corrective actions, different behavior of Total Errors (A in Fig. 3) can be observed. If assigning skilled workers is very efficient in this case, the S-shaped behavior (D in Fig. 3) can be achieved, thereby offsetting the effect of the self-reinforcing feedback. Otherwise, Total Errors continue to undergo exponential growth (E in Fig. 3).

In this regard, DPM emphasizes understanding of the system structure in order to effectively control the resultant project dynamics, thereby suggesting a system structure-oriented approach. In other words, since behavior arises from system structure, the behavior of particular interest can be controlled by changing the system structure. As such, a clear understanding of system structure is required, particularly when corrective actions are considered.

### 6.3 Incorporation of Time Delay

Another characteristic of DPM is its appreciation of time delay. Dynamics behavior originating from the system structure can be more complex when time delay is outstanding. One of the most prominent forms of time delay is latency [28]. Continuing with the previous pile installation example, suppose that one of the piles is erroneous and has not yet been identified. In this case, even though eight piles are apparently completed, actually achieved performance is the completion of seven piles because the hidden one will be addressed at a later stage of the project, (i.e., latency) [28]. In this case, succeeding tasks, such as installing a column on this pile installation, may be already completed. If the hidden error is discovered after installing the column, the column may need to be removed before the erroneous pile, followed by the installation of a new pile and column. This creates increased additional work compared to the previous case and consequently makes the project more complex, which intensifies feedbacks. In addition, this latency involves a lot of waste, which can't be captured by only the increased work scope. For example, a lot of time can be used for request for information (RFI) to correct this erroneous pile and to decide what steps should be taken. Further, an additional quality management process should be taken in order to ensure its quality. Resource allocation should be rearranged to deal with such sudden and emergent work. In the worst case, a derivative activity can occur if the subcontractor for the piling activity has already been withdrawn. Thus, this 'invisible' effort used to address latency should be captured and minimized because it will eventually consume significant time and cost. In an effort to overcome this issue, DPM suggests that value, the ratio of the project requirements to the operational efforts [29], should be monitored and managed through the life cycle of the project. Value measures the operational efficiency by showing the extent the efforts contributed to the project requirements. In order to increase value, the method of minimizing the efforts should be investigated since the project requirements are almost constant. Particularly, the efforts caused by the performance gap and change like those in the pile installing example should be minimized because they do not add any value. DPM suggests a method for capturing and representing such efforts, but it is beyond the scope in this chapter. The interested readers can find it in [30].

On the other hand, time delay can also take place in the system structure and affect the intended impact of corrective actions. Continuing with the example in Fig. 3, suppose that skilled workers need to be shifted to the pile installation activity in order to deal with the scope increase caused by erroneous piles, but cannot be due to their shortage. In this case, another system structure that will represent other options such as hiring new skilled workers can be added. This option can be effective in producing the intended behavior, such as an S-shape curve in Total Error (A in Fig. 3). However, if it is not the case (e.g., due to the difficulty in hiring qualified workers or the excessive time taken for this hiring process), another change to the structure needs to be undertaken until the intended behavior is obtained. This iterative process will eventually lead to appropriate corrective action design.

## 7 Conclusions

Computer simulation has been utilized as an effective planning and analysis tool in the construction engineering and management area over the past decades. DES has dominated the development of construction simulation by virtue of operational details that are not readily provided by traditional network-based approaches. Under the pursuit of management at the lowest possible level encouraged by the decomposition-based approaches, DES has been primarily applied to address operational issues, by taking a narrow focus and partial view of a project. However, DES can sometimes provide unrealistic estimations, particularly when operational settings are significantly altered by other related operations. SD has great potential to address this limitation; however, it has received little attention in the construction engineering and management area.

In order to examine the opportunities and benefits of SD modeling, this chapter introduced DPM, which has been successfully applied to diverse infrastructure and building construction projects. Particularly, this chapter provided the following three theoretical foundations of DPM: a holistic approach, including planning and control functions of project management; a system structure-oriented modeling approach that enables deeper understanding of dynamic behavior and devising effective corrective actions; and the incorporation of control time delay that can make dynamic behavior more complex.

With these three theoretical foundations, DPM can successfully deal with dynamic complexities in construction projects that are not easily addressed by network-based approaches or DES, such as iterative cycles caused by errors and changes. However, as an SD-based approach, DPM inherits some of the weaknesses of SD modeling such as the lack of operational details or limitations in representing heterogeneous type of entities flowing into a stock. Therefore, the authors have been working on a hybrid simulation combining DES and SD as the next generation of DPM. This development will be reported in the authors' subsequent papers.

## References

1. Pritsker AB, O'Reilly JJ (1999) Simulation with visual SLAM and AWESIM. Wiley, New York
2. Pegden C, Shannon R, Sadowsky R (1995) Introduction to simulation using SIMAN. McGraw Hill, OH
3. Banks J, Carson II JS, Nelson BL, Nicol DM (2000) Discrete-event system simulation. Englewood Cliffs, Prentice-Hall, New Jersey
4. Law AM, Kelton DM (1999) Simulation modeling and analysis. McGraw-Hill, New York
5. Brailsford SC, Hilton NA (2000) A comparison of discrete event simulation and system dynamics for modelling healthcare systems. In: Proceedings of operational research applied to health services, 18–39
6. Sterman JD (2000) Business dynamics: systems thinking and modeling for a complex world. McGraw-Hill, Boston

7. AbouRizk SM (2010) Role of simulation in construction engineering and management. J Constr Eng Manage 136(10):1140–1153
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):76–83
9. Peña-Mora F, Han S, Lee S, Park M (2008) Strategic-operational construction management: hybrid system dynamics and discrete event approach. J Constr Eng Manage 134(9):701–710
10. Walsh KD, Hershauer JC, Walsh TA, Tommelein ID, Sawhney A (2002) Lead time reduction via pre-positioning of inventory in an industrial construction supply chain. Winter Simul Conf 2002:1737–1744
11. Williams T (2002) Modelling complex projects. Wiley, New York
12. Howell GA (1999) What is lean construction. In: Proceeding of the 7th annual conference of international group for lean construction, Berkeley, CA
13. Garcia-Fornieles JM, Fan IS, Perez A, Wainwright C, Sehdev K (2003) A work breakdown structure that integrates different views in aircraft modification projects. Concurr Eng Res Appl 11(1):47–54
14. Koskela LJ, Kagioglou M (2005) On the metaphysics of production. In: Proceeding of the 13th annual conference of international group for lean construction. Sydney, Australia
15. AbouRizk SM, Halpin DW, Lutz JD (1992) State of the art in construction simulation. In: Proceedings of the 1992 winter simulation conference, pp 1271–1277
16. Ondash SC, Maloney S, Huerta J (1988) Large project simulation: a power tool for project management analysis. In: Proceedings of the 1988 winter simulation conference los angeles. pp 231–239
17. Rodrigues A, Bowers J (1996) The role of system dynamics in project management. Int J Proj Manage 14(4):213–220
18. Morris PWG, Hough GH (1987) The anatomy of major projects: a study of the reality of project management. John Wiley & Sons Ltd, Chichester
19. Davidson FP, Huot J (1991) Large scale projects - management trends for major projects. Cost Eng 33(2):15–23
20. Lee S, Peña-Mora F, Park M (2005) Quality and change management model for large scale concurrent design and construction projects. J Constr Eng Manage 131(8):890–902
21. Martin R, Raffo D (2001) Application of a hybrid process simulation model to a software development project. J Syst Softw 59:237–246
22. Forrester J (1961) Industrial dynamics. Pegasus Communications, Waltham
23. Ford A (1999) Modeling the environment. Island Press, Washington
24. Sterman JD (1992) System dynamics modeling for project management. Working paper, MIT, Cambridge
25. Park M, Peña-Mora F (2003) Dynamic change management for construction: introducing the change cycle into model-based project management. Syst Dyn Rev 19(3):213–242
26. Han S, Love PED, Peña-Mora F (2011) A system dynamics model for assessing the impacts of design errors in construction projects. Mathematical and Computer Modelling advance online publication 22 June, doi:10.1016/j.mcm.2011.06.039
27. Ogata K (2002) Modern control engineering. Prentice Hall, Upper Saddle River
28. Lee S, Peña-Mora F, Park M (2006) Reliability and stability buffering approach: focusing on the issues of errors and changes in concurrent design and construction projects. J Constr Eng Manage 132(5):452–464
29. Thiry M (1997) Value management practice. Project Management Institute, Atlanta
30. Han S, Lee S, Peña-Mora F (2012) Identification and quantification of non-value-adding effort from errors and changes in design and construction projects. J Constr Eng Manage 138(1):98–109