Mathematical and Computer Modelling 57 (2013) 2044–2053

Contents lists available at SciVerse ScienceDirect

Mathematical and Computer Modelling

journal homepage: www.elsevier.com/locate/mcm

A system dynamics model for assessing the impacts of design errors in construction projects

Sangwon Han [a,*], Peter Love [b], Feniosky Peña-Mora [c]

[a] Department of Architectural Engineering, University of Seoul, Seoul, Republic of Korea
[b] School of Built Environment, Curtin University of Technology, Perth, Australia
[c] School of Engineering and Applied Science, Columbia University, NY, United States

ARTICLE INFO

Article history:
Received 30 March 2011
Received in revised form 14 June 2011
Accepted 15 June 2011

Keywords:
Design errors
Rework
Design change
Schedule revision
Simulation
Schedule delay
Cost overrun

ABSTRACT

Design errors leading to rework and/or design changes are considered to be the primary contributor to schedule delays and cost overruns in design and construction projects. While design errors are deemed prevalent, most design and construction firms do not measure the number of errors they create, thereby having limited knowledge regarding their mechanism to undermine project performance. To address this, a system dynamics model has been developed to capture the dynamics of design errors and systematically assess their negative impacts. This paper reports on the development of the model, and its application to a university building project. The results indicate that design errors can significantly delay project schedule in spite of continuous schedule recovery actions taken by construction managers. The case study also shows that schedule pressure can propagate the negative impact of design errors to numerous construction activities, including those that are not directly associated with the errors. Finally, the case study confirms that the developed model can more rigorously assess the negative impact of design errors, which is often underestimated by practitioners. Based on these results, it is concluded that the developed model can assist project managers in better understanding the dynamics of design errors and recovering delayed schedule, particularly under schedule pressure.

1. Introduction

Despite advances in construction equipment and management techniques, major schedule delays and substantial cost overruns persist in design and construction projects [1–5]. US General Accounting Office [6] reported that its 20 civil infrastructure projects across 17 states, with estimated total cost ranging from $205 million to $2.6 billion, experienced significant cost overruns ranging from around 40% to 400%. This trend is not limited to projects in the United States. Latham [7] reported that only 70% of projects in the United Kingdom were delivered within 5% of the tender cost and only 38% within 5% of the tender program. Bromilow [8] also claimed that only one-eighth of Australian building contracts were completed within the scheduled completion dates and that the average schedule overrun exceeded 40%. Flyvbjerg et al. [9] analyzed 258 mega-projects undertaken across 20 countries, concluding that cost overruns were found in 90% of these projects; and that such cost escalation is not a new phenomenon, but has persisted over the past 70 years. This broad range of research is evidence that schedule delay and cost overruns are the rule rather than the exception in the construction industry [5].

* Corresponding author.
E-mail address: swhan@uos.ac.kr (S. Han).

0895-7177/$ – see front matter
doi:10.1016/j.mcm.2011.06.039

Rework has been identified as an endemic problem in construction and engineering projects, and a major contributor to schedule delays and cost overruns [10]. Rework has been defined by Love [11] as ''the unnecessary effort of redoing a process or task that was incorrectly implemented the first time''. Rework, on average, contributes to 52% of total cost overrun, and can increase schedule overrun by 22% [10]. It has also been found that 5%–20% of the contract value can be attributed to rework in construction and engineering projects [12,10].

A major contributor to rework is design error. When an error is identified, it often requires rework to be undertaken, which involves additional time and resource expenditure [13,14]. Unfortunately, regardless of an individual's skill level, experience or education, errors may occur at any time due to the physiological and psychological limitations of humans [15]. Reason [16] contends that it is often the most qualified and highly competent individuals that commit errors with the most detrimental consequences. In general, design and construction firms do not measure the number of errors they create and, in particular, they generally fail to undertake appropriate design reviews, verifications and audits [17,18]. Accordingly, errors are often not identified immediately, but tend to transpire after a period of incubation in the system [19]. After some time, these errors are detected and the need for rework is identified, increasing the amount of remaining work [20–22]. The degree of rework required grows when errors remained undetected for longer periods of time [23].

Tsang and Zahra [24] suggest that the causes and effects of errors are not unidirectional or linear, but are reciprocal and looped in their relationships. In the pursuit of error and rework reduction, it is necessary to understand how such relationships emerge and interact with one another [25]. Based on this recognition, this paper aims to develop a system dynamics model to assist in better understanding the complex mechanism of design errors in which they damage project performance.

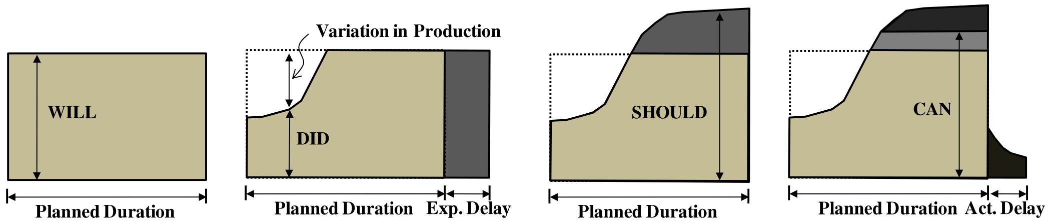
2. Design errors in construction projects

Human error can be defined as ''the failure of planned actions to achieve their desired goal, where this occurs without some unforeseeable or chance intervention'' [26]. Erroneous decisions made during design can occur due to impaired human cognition [27], particularly when designers experience workplace stress due to schedule and cost pressures [28]. Designers' cognitive processes can propagate throughout projects they work on and the wider organization, and this may increase the occurrence of errors [23]. Designers may omit to: involve others in design decisions, inform others of assumptions made, elicit other's needs and schedules, or understand the history of problem solving in a replicated design [27]. Love et al.'s [29] phenomenological approach proves that the uncertainty and inevitability of error are not perceptions, but are a reality for design consultants, resulting from the exogenous factors influencing their ability to perform tasks effectively. These factors include schedule pressure, design fees, client procurement strategy and skilled labor supply. In practice, many design and construction organizations pay limited attention to errors and the resulting rework or failures that may occur [17,30,25,29]. The size and complexity of a project, the number of professionals involved in its design and construction, and the complexities of procurement and price determination for services contribute to the potential for 'iatrogenic' impairment [23]. Other systemic problems may include lack of design reviews, checks and verifications, re-use of specification and details, unrealistic schedules, understaffing, and lack of project governance [29].

Triggered by these various factors, design errors can significantly lower project performance by generating rework, requiring additional time and resource expenditure. Furthermore, if errors are discovered during construction, additional time and resources may be required for demolition of incorrectly constructed components. Because of this additional time and cost, construction managers tend to avoid rework on problematic activities by modifying designs and specifications [1]. Particularly in highly uncertain circumstances, there is an over-reliance on scope changes to solve problems that may arise during construction, installation and commissioning [23]. However, if impacts of sudden changes in scope or design are not thoroughly assessed, they often induce additional problems by significantly altering project execution sequences and/or resource profiles. Burati et al. [31] found that 79% of rework costs arising in industrial engineering projects were the result of design changes, errors and omissions. Similarly, Love [11] revealed that design change orders resulting in rework can account for as much as 50% of project cost overrun.

Not only do design errors result in rework and/or sudden design change, they are also one of the main reasons for unreliable progress monitoring, which causes recovery actions taken by project managers to be ineffective. Cooper [20] contended that undetected rework is the main driver of discrepancies between real progress and perceived progress. Since project managers take schedule recovery actions based on perceived progress, the effectiveness of recovery actions diminishes as the gap between perceived and real progress widens. This in turn lowers the chances of on-time project completion. As hidden rework is discovered, construction managers realize that real progress is less than they had perceived, and that there is much more work remaining than was perceived. This can cause schedule pressure amongst project managers, inducing latent conditions where further errors are likely.

In an effort to meet a project's schedule completion date, additional resources may be employed; however, such action may lead to a contradictory effect [32]. By exceeding the limits of concurrency, complexity increases and tasks are delayed, particularly when revisions, repairs and rework occur [33]. Pate and Cornell [34] suggests that schedule pressure not only increases the probability of errors occurring (e.g., erroneous execution in the construction stage), but also decreases the chances that they are detected using regular procedures. Design errors that may be deemed minor in nature are likely to be overlooked due to the time that it would invariably take to correct them [23].



(a) WILL. (b) DID. (c) SHOULD. (d) CAN.

Fig. 1. Schematic model for understanding the dynamics of design errors.

3. Model building

To create a robust model for assessing the impact of design errors on project performance, this paper first develops a schematic model that captures the dynamics of design errors. Then, based on the dynamics identified, a system dynamics model is introduced to further explain the complex mechanism of design errors, to analyze the way in which they damage project performance, and to measure the degree of this impact.

3.1. Schematic model

The duration of an activity can be estimated by dividing the activity scope (i.e., the amount of work) by the production rate at which we WILL complete per time unit such as daily production (Fig. 1-(a)). For example, if 50 units of residential steel doors are to be installed and the nominal work rate of a given crew configuration is 5 units/day, 10 days will be the expected duration of the door installation process.

However, as established above, if design errors (e.g., an incorrectly positioned door where it will intersect with pipelines) are not immediately identified, they are likely to be discovered during the construction stage and necessitate additional effort for rework. As a certain amount of effort would be wasted on rework (and sometimes also on demolition), this late error discovery may induce 'variation in production', which is the difference between what we WILL do and what we actually DID (Fig. 1-(b)). In order to compensate for lower production rates at early stages caused by 'variation in production', a longer duration than initially planned ('planned duration and expected delay') would be required to finish the work. Once the finish time for a given critical activity is delayed, this can delay the start time of its successor activities, which can trigger additional problems such as relocation of labor and procurement of resources. Considering this, it is not surprising that variation, especially of activity duration, is the main factor increasing the volume of non-value adding activities, thereby impairing project performance [35].

In order to avoid this, construction managers would not just oversee the expected delay, but take schedule recovery actions in order to increase production rate and complete the activity within its planned duration [36–39] (Fig. 1-(c)). These schedule recovery actions may include assigning additional workers, hiring more productive equipment, or applying an overtime policy [39]. Managerial actions are generally adopted in an attempt to avoid expected delay, but it should be noted that these actions may increase schedule pressure. Schedule pressure is calculated by dividing what we SHOULD in order to maintain a deadline with what we CAN do (Fig. 1-(d)). If what we SHOULD do is much greater than what we CAN do, construction managers tend to cut corners, which might mean direct omissions, but frequently it is as simple as not checking one's work to the degree of detail necessary to find most of the error [40]. Therefore, cutting corners often compromises quality standards, and the associated quality problems are not easily discovered until late in a project. In these cases, significant rework is often required.

Therefore, in spite of a manager's continuous effort to maintain the planned duration, 'actual delay' may take place and may increase the volume of non-value adding activities [35]. In addition, if errors are made and not immediately detected under schedule pressure, but identified after work has begun on a successor activity, execution of the successor activity may then suffer from 'variation in production' in its early stages due to the late discovered errors. Then, this successor activity would also be executed under schedule pressure in order to meet its planned duration and finally result in erroneous execution and late discovery. As such, if design errors are not thoroughly addressed, their negative impact propagate through numerous construction activities. Accordingly, any variation of an activity in a construction schedule may impact the remaining activities, even if the variation does not involve these activities directly [41,14]. This is one of the main reasons why construction managers continuously work under schedule pressure and experience schedule delays despite their best effort to recover delayed schedules [13].

3.2. System dynamics model

A system dynamics (SD) model was developed based on the dynamics of design errors identified through the schematic model. As shown in Fig. 2, this model evolved from highly established and validated models including those developed by Cooper [42], Richardson and Pugh [43], Abdel-Hamid [44], Ford and Sterman [45], Rodrigues and Williams [22],

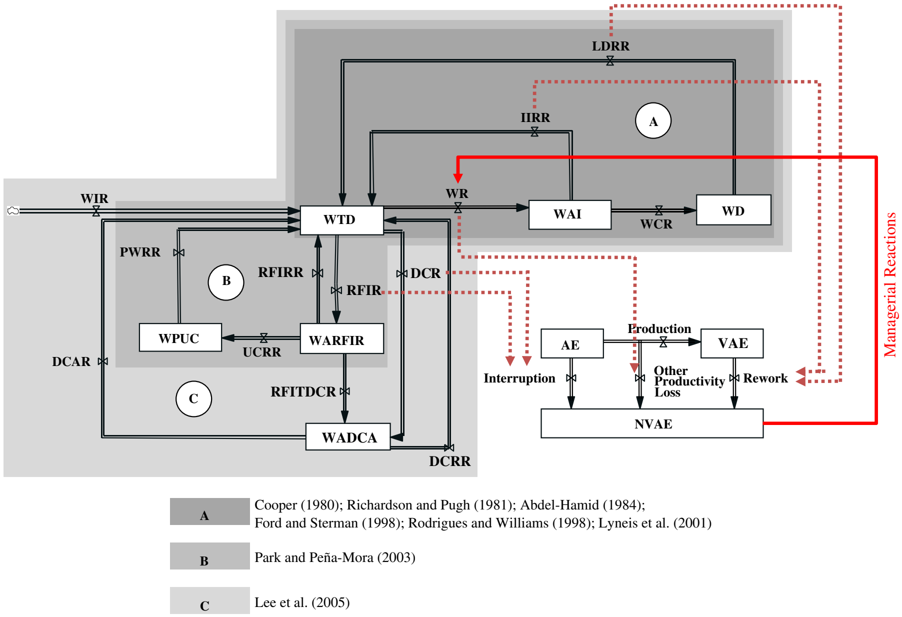


Fig. 2. System dynamics model [expanded from [47]; Evolved from [1,46,22,45,44,43,42]].

Lyneis et al. [46], Park and Peña-Mora [1] and Lee et al. [47]. The developed model consists of several sub-modules including 'generic work execution', 'effort', 'precedence relationship', 'productivity', 'resource', 'progress measurement' and 'managerial control'. Among these modules, the 'generic work execution' module (Fig. 2) is a key component, underpinning the entire model structure.

The 'generic work execution' model captures the dynamics of work execution within an activity. There are six possible states of any work item; namely WTD (Work To Do), WAI (Work Awaiting Inspection), WD (Work Done), WARFIR (Work Awaiting Request For Information Reply), WPUC (Work Pending until Upstream Correction) and WADCA (Work Awaiting Design Changes Approval). Available work items at a given time are introduced to the WTD through WIR (Work Introduction Rate), which is regulated by imposed precedence relationships with related activities (e.g., Start-to-Start or Finish-to-Start) and/or physical constraints within the given activity (e.g., second floor activity can start after completion of the first floor activity). Introduced work is initially stored in WTD. Work items in WTD are executed and then moved to WAI through WR (Work Rate), which is the product of the level of resources assigned and their productivity. Once work items are moved to WAI, they are inspected and only correctly executed work items are moved to WD through WCR (Work Completion Rate), while incorrectly executed work items are returned to WTD through IIRR (Immediately Identified Rework Rate). This is the basic structure of the 'Rework Cycle' [20].

However, work items in WTD are not always ready to be executed. A representative example is discovery of design errors during construction (e.g., site conditions are not as expected and therefore design is not appropriate). In this situation, construction managers send RFIs (requests for information) to the design team and the work items related to the design errors cannot be executed until these design errors are corrected. This process is represented in the model through the movement of some work items from WTD to WARFIR through RFIR (Request For Information Rate). Once clarification from the design team arrives, the work related with design errors can be executed. This process is represented by moving work items from WARFIR to WTD through RFIRR (Request For Information Reply Rate).

On the other hand, regardless of design errors, RFI can be requested during construction when execution errors related with a predecessor activity are discovered. In this case, the current activity may be disrupted until the previous activity is corrected. This is represented by two concurrent processes: the movement of work items from WARFIR to WPUC through UCRR (Upstream Correction Request Rate) in the current activity and the movement of work items from WD to WTD through LDRR (Late Discovered Rework Rate) in the predecessor activity. Once the predecessor is corrected, the current activity is ready for execution. This is captured by the movement of work items from WPUC to WTD through PWRR (Pending Work Release Rate).

Sometimes, RFIs may result in design changes, particularly when it is not easy to correct design or execution errors made during a predecessor activity. In this case, work items in WARFIR move to WADCA through RFITDCR (Request For Information To Design Change Rate). Even when there are neither design errors nor execution errors, sudden design change orders (primarily due to owners' or designers' late request) can prevent execution of the current activity. In this case, some work items in WTD move to WADCA through DCR (Design Change Rate).

Once a change order is issued, the change control board (CCB) carefully assesses the feasibility of the proposed change and makes a decision regarding whether or not the change should be implemented. Upon arrival at a CCD decision, execution of the current activity can resume. This is represented by the movement of work items from WADCA through either DCAR (Design Change Approval Rate) or DCRR (Design Change Reject Rate). When sudden design changes are approved during the execution of an activity, some work items already completed may need to be reworked if they are based on a superseded design document. This results in a transfer of some work items from WD to WTD through LDRR. As such, the quantity of work items in a given status at any point in time can be mathematically formulated as follows.

$$\begin{aligned}(\mathrm{d}/\mathrm{d}t)\ (\mathrm{WTD}[i]) \ =\ & \mathrm{WIR}[i] - \mathrm{WR}[i] + \mathrm{IIRR}[i] + \mathrm{LDRR}[i] - \mathrm{DCR}[i] + \mathrm{DCAR}[i] + \mathrm{DCRR}[i] \\ & - \mathrm{sum}_{j=1\ldots n}(\mathrm{RFIR}[i,j]) + \mathrm{sum}_{j=1\ldots n}(\mathrm{RFIRR}[i,j]) + \mathrm{sum}_{j=1\ldots n}(\mathrm{PWRR}[i,j])\end{aligned}$$

$$(\mathrm{d}/\mathrm{d}t)\ (\mathrm{WAI}[i]) = \mathrm{WR}[i] - \mathrm{WCR}[i] - \mathrm{IIRR}[i]$$

$$(\mathrm{d}/\mathrm{d}t)\ (\mathrm{WD}[i]) = \mathrm{WCR}[i] - \mathrm{LDRR}[i]$$

$$(\mathrm{d}/\mathrm{d}t)\ (\mathrm{WARFIR}[i,j]) = \mathrm{RFIR}[i,j] - \mathrm{RFIRR}[i,j] - \mathrm{UCRR}[i,j] - \mathrm{RFITDCR}[i,j]$$

$$(\mathrm{d}/\mathrm{d}t)\ (\mathrm{WPUC}[i,j]) = \mathrm{UCRR}[i,j] - \mathrm{PWRR}[i,j]$$

$$(\mathrm{d}/\mathrm{d}t)\ (\mathrm{WADCA}[i]) = \mathrm{DCR}[i] + \mathrm{sum}_{j=1\ldots n}(\mathrm{RFIDCR}[i,j]) - \mathrm{DCAR}[i] - \mathrm{DCRR}[i]$$

where i = current activity, j = predecessor activity, and $i, j \in \{1, 2, 3, \ldots, n\}$.

As mentioned previously, WR is determined by the quantity of resources assigned, and their productivity in this module. In practice, when actual progress lags behind the planned progress, construction managers usually expedite the work rate in order to maintain progress in accordance with the planned project schedule. This model incorporates this managerial reaction. Therefore, WR in this model is not set to be a single, constant value, but is a dynamic value that can vary over the duration of a given activity. For example, if the perceived schedule is behind the planned schedule, the developed simulation model would increase the WR in imitation of recovery actions adopted by construction managers in practice (e.g., applying an overtime policy). Such an incorporation of managerial actions into the simulation model is a key to increase realism [36,48,39]. The WR is also affected by the current progress due to the learning effect, which describes productivity improvements through repeated execution of a task. In addition, prolonged overtime may introduce the fatigue effect, which represents productivity deterioration due to weariness. Based on this recognition, WR at a given time in a give activity is calculated as follows.

$$\mathrm{WR}[i] = \mathrm{AR}[i] \times \mathrm{OT}[i] \times \mathrm{LE}[i] \times \mathrm{FE}[i].$$

AssignedResource (AR), OverTime (OT), LearningEffect (LE) and FatigueEffect (FE) at a given time for a given activity are calculated in other sub-modules such as managerial control, productivity and progress measurement. These elements are not fully explained in this paper due to limited space.

Linking with the generic execution module, the effort module was developed to estimate the amount of non-value added effort (NVAE) due to design errors, which is the difference between the assigned effort (AE) and the value added effort (VAE). For this, the effort module captures the amount of interruption via the work interrupted by the change order process (DCR) and the RFI process (RFIR). Furthermore, it measures other productivity loss by comparing actual work rate (WR) and nominal work rate. It also quantifies rework through the problems instantly identified by the inspection process (IIDR) and those lately discovered by the succeeding activities (LDRR). The total amount of wasted efforts due to design errors is calculated by integrating the effort squandered by interruption, other productivity loss and rework and then affects the work rate (WR) again by managerial reactions taken in order to meet the planned schedule.

3.3. Model testing

The developed model has been validated and verified in terms of its usefulness for assessing the impacts of design errors on project performance. Both the structure and behavior of the developed model was tested extensively under three distinct criteria: (1) suitability for purpose; (2) consistency with reality; (3) utility and effectiveness as suggested by Richardson and Pugh [43]. An example of a method to test consistency of the model behavior with reality is an extreme condition test, which was conducted to determine whether the developed model behaved in a realistic manner under extreme values or policy. When no design errors were fed to the model (i.e., one extreme condition), the simulation result was exactly identical to the target schedule. Note that this model does not account for the impacts of other external factors such as weather or economic situation. Exclusion of these factors should not reject the validity of this model because a model is considered valid only for the purpose for which it is built, and not in absolute terms [49]. A test used to prove the effectiveness of the model is a behavior reproduction test, which assesses the model's ability to reproduce the behavior of interest. The details of the behavior reproduction test are provided through a case study in the following section.

4. Case study: a university building project

To test the applicability of the developed simulation model in terms of assessing the impact of design errors on project performance, a university building project was selected as a case study. General information about the project is summarized in Table 1.

Table 1
General information about the case study project.

Classification	Description
Scope	- Five-story building (four above-ground and one under-ground) - Total area: 154,000 ft^2 - 18 classrooms, study areas, 24 interview rooms, an accountancy center, a market trading lab, and a 300-seat auditorium
Structure	- Structural steels and concrete footings - Enveloped by aluminum curtain wall, brick and stone veneer with masonry
Budget	- Total: $62 million - $42 million for construction - $20 million for site preparation, equipment, professional fees and so forth
Construction schedule	- Original: March 2005 to July 2007 (30 months) - Revised (initial): May 2006 to May 2008 (24 months) - Delay and reduction of schedule due to approval/funding problems
Additional requirement	- The university's first leadership in energy and environmental design (LEED) certified building project - Energy efficient windows, water conservation techniques, green roof systems, photovoltaic arrays, native plants, and recycling waste from construction

It is the university's long-term strategy that all future buildings should be LEED certified. In this sense, acquisition of the LEED certification is one critical success factor in this project as a ''pilot building project''. Typically, the university does not hire an external construction manager for projects, as an in-house project management team is able to perform the management task. However, in this case, the university hired an external construction manager to deal with additional complexities and risks related to acquisition of the LEED certification, and to reduce the construction schedule by 6 months in response to approval and funding problems.

4.1. Current progress

In order for a model to be utilized for assessing the impacts of design errors, the model first needs to reproduce current progress as closely as possible. The model can then be utilized to analyze the way in which design errors lower current performance and to forecast future performance. To this end, as of November 1st 2007, current progress was carefully analyzed by interviewing key project personnel (including the university project manager, construction manager, superintendent and scheduler) and reviewing relevant project documents such as a daily log, non-conformance report, RFIs and change order logs.

In the pursuit of timely completion for this project, the construction manager closely monitored the project. While it is normal to assign one or two personnel for progress monitoring for a project of this size, four personnel were responsible for progress monitoring, including a member of the construction management group, the project manager, the junior engineer and the superintendent. As a result of independent monitoring by multiple parties, construction error potential was relatively low in this project.

For timely progress measurement and schedule revision, three regular project meetings were held. First, foreman meetings were held every morning to monitor daily tasks and prevent potential disruption between related trades. Second, the construction manager and university project manager facilitated a meeting with project managers from each contract on a weekly basis. Finally, large group meetings were held once a month, usually running for one and a half days.

Although the project management board invested their best efforts to effectively manage the project through methods described above, its actual progress was significantly delayed. As shown in Table 1, the initial planned project completion date was May 13th 2008. Extensive float was included in the initial schedule. Most of the activities had a range of 7 to 40 days float. However, due to unexpected schedule delays mostly resulting from design errors, its substantial completion was delayed to August 1st 2008, leaving the university only three weeks to move into the new building. This means less than one week per floor was allowed to install furniture and technology after substantial completion. Furthermore, since the schedule delays used up almost all float time allowed, the construction manager compressed every possible activity in order to meet the revised construction deadline (i.e., August 1st 2008). In addition, in order to prevent any further delay, the construction manager attempted to start all remaining activities as early as possible, even activities with plenty of float time. Because of this time constraint, some out-of-sequence activities were undertaken. For example, the interior walls were installed before the steel roof was fireproofed. On fireproofing the steel roof, the interior walls had to be protected and this significantly reduced workers' productivity.

4.2. Identified reasons of the schedule delay

Several causes of schedule delays in the project were identified through interviewing key project personnel, including the construction manager, project manager for the university, the designer, and several superintendents. Project documents were also examined.

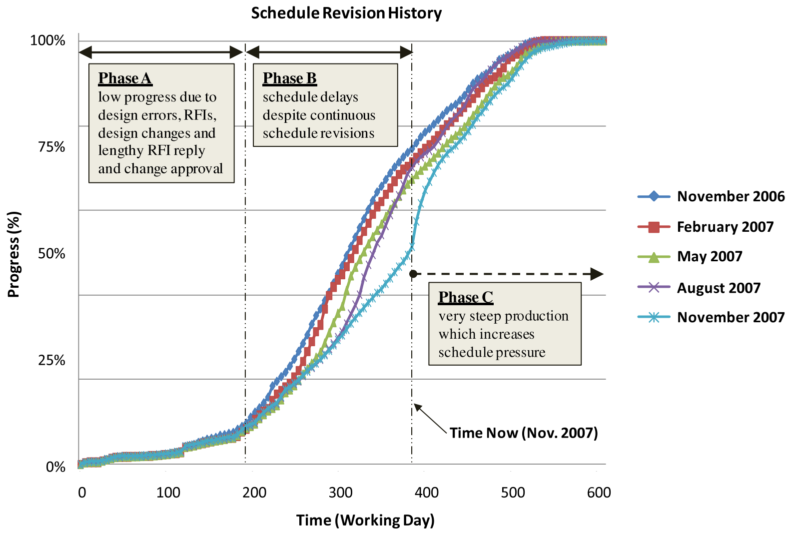


Fig. 3. History of schedule revision in the BIF project.

(1) Design errors

While schedule delays in the project partially resulted from unforeseen weather conditions and unexpected ground conditions, the majority of the delays resulted from poor quality of design documents. An extreme example is that approximately 6 months were consumed in fixing design errors in construction documents for exterior walls. During this time, no work could be done in the left wing of the building. Another extreme example was double-paned windows installed on the exterior walls. Initially, 4-inch concrete blocks were designed to be placed between the double-paned windows, but were later found to be structurally insufficient to support the loads on the walls. It took another 6 months to redesign the wall, and no drywall installation could be executed for the interior of the building during that time.

(2) Frequent change orders

Another key factor impacting the schedule in this project was change orders. One major source for change orders was the defects of construction drawings (i.e., design errors). For example, the green roof was found to be structurally inadequate to support the quantity of soil it was intended to support. These types of errors were abundant in this project. Many design errors were discovered after construction had started, and significantly delayed progress and increased the cost of change orders. So far, more than 240 change orders were issued and most of them were required to rectify design errors. Change orders costing $4 million were approved, with a quarter of this amount attributed to design errors and omissions.

(3) Long RFI and change approval time

It was found that long RFI and change approval time also resulted in schedule delays in the project. Loss of key project personnel like construction managers or designers can be highly disruptive to communication and coordination [50]. In the case project, two of the original architects were removed from the project after the design had been completed and construction had begun. Replacement architects were not fully familiar with the design. This posed problems when contractors submitted RFIs because the new architects could not respond quickly. They needed to accurately understand the previous architects' work before responding to the RFIs. In addition to this, the university bureaucracy was identified as another cause of significant delay. The university bureaucracy is necessary to ensure that the resulting facility meets the satisfaction of all stakeholders, but from a management perspective, the various levels of bureaucracy, often in disagreement among themselves, add an additional layer of complexity to the project. As a result, the average time for a change order to be processed by the university was 88 days. This means that the construction of any related component is held up almost three months whenever a change order is required.

4.3. Schedule revision history

Fig. 3 shows the schedule revision history for the case project from November 15th 2006 to November 1st 2007. The project management team revised the schedule every month based on cumulative actual progress. Thus, during this period, the team made 13 revisions on the initial schedule. In order to avoid visual complexity, Fig. 3 shows progress at quarterly intervals.

As observed in most university building projects, the case project was executed under a very strict schedule for opening for fall semester 2008, with classes for this building already scheduled. Thus, whenever the schedule was revised, the project management team attempted to maintain the planned deadline as closely as possible. Due to this nature, the further revision of the schedule resulted in the progress *S*-curve becoming 'lazier'. In other words, progress at later stages became

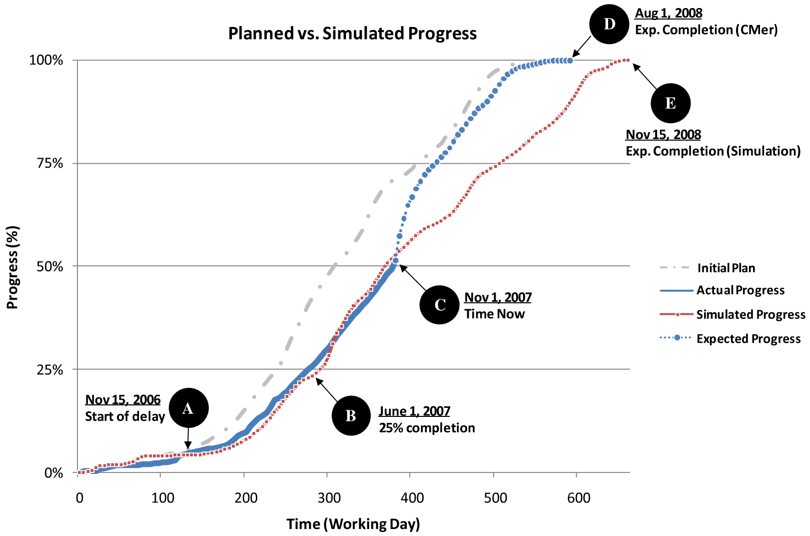


Fig. 4. Comparison of planned vs. simulated progress.

increasingly steeper, implying work was being performed under higher schedule pressure in order to recover wasted effort related to design errors at earlier stages of the project.

As denoted by 'A' in Fig. 3, the progress of the earlier stage was very slow, because of (1) many late discovered design errors, (2) numerous RFIs and change orders, and (3) slow RFI replies and change approvals. Therefore, the project management team revised the schedule in order to keep the delayed progress on track. However, Fig. 3 shows that these revisions were not very effective in recovering the delayed progress. As denoted by 'B' in Fig. 3, the actual progress was repeatedly behind the revised progress. This was mainly triggered by execution under increasing schedule pressure, which not only increases the occurrence of errors, but also decreases the probability that of detection through regular procedures [34].

One common feature observed in the schedule revision history is the project management team's expectation of a very steep production rate (as shown in 'C' in Fig. 3), which may introduce additional risk such as productivity loss, execution errors, and incubation of these problems. The project management team continuously encountered risk of schedule delay, despite repeated revision of the schedule and their best efforts for timely completion. This fact may imply that the project management team underestimated the impacts of design errors and the additional risk resulting from schedule pressure, which is the latent condition for error generation.

4.4. Model-based performance estimation

Fig. 4 shows a comparison of the initial schedule (developed at the beginning of construction), actual progress (as of November 1st 2007), progress forecasted by the project management team, and simulated progress.

As shown in Fig. 4, the actual progress is far behind the planned progress. As denoted by 'A' in Fig. 4, the project delays began when 5% of the total progress was completed. This is mainly because detection of design errors began from that point in time. Also, Fig. 4 shows very slow progress until about the 200th working day, and the very slow progress at this stage is attributed to the combined effects of late discovered design errors and long RFI time resulting from change of key designers. Its initial planned construction duration was 522 working days, but as of the 280th working day ('B' in Fig. 4 which denotes more than half of the total construction duration), its actual progress was approximately 25%. As of November 1st 2007 ('C' in Fig. 4), actual progress was approximately 50%. Based on this actual progress, the project management team revised the schedule and tried to condense every activity where possible, in order to meet the revised construction deadline (August 1st 2008; 'D' in Fig. 4). However, the developed simulation model results show that based on the actual performance, the project would be completed by November 15th 2008 (i.e., 3.5 months later than the planned completion), assuming the project management team were to maintain the same control policy. The major reason for this pessimistic estimation is that the developed model incorporates the impacts of hidden design errors on the remaining work, and additional risk resulting from higher schedule pressure.

Certainly, this pessimistic estimation is not acceptable to the university, as the classes for this building are scheduled from August 2008. If the building were not completed by August 2008, the university would not provide the scheduled classes to its students. Therefore, it should be certainly completed by August 2008. However, according to the simulation results based on current progress as of November 2007, the progress would reach about 90% by August 2008.

At last, despite the extensive use of shift work, the building was partially opened on August 2008 with only some teaching facilities available, due to urgent requirements for teaching space (e.g., classrooms and laboratories). Opening other facilities including staff rooms and study areas was postponed. After the building was opened, remaining work continued at night and over weekends during the semester, and the building was eventually completed in December 2008. While more verification effort is required for the application of the developed model, the case study shows that the model has a great potential in aiding construction managers to assess negative impact of design errors in a more systematic way.

5. Conclusions

Design errors are a major contributor to rework, which ultimately leads to schedule delays and cost overruns in design and construction projects. While eradication of all design errors is desirable to dramatically enhance project performance, this is practically impossible due to the physiological and psychological limitations of humans. Therefore, it is imperative to systematically assess the impact of design errors through understanding their mechanism to undermine project performance. In an attempt to address this issue, this paper introduced a system dynamics model that can assess the impacts of design errors based on the recognition that the causes and effects of committing errors are not unidirectional or linear, but are reciprocal and looped in their relationships.

Application of the model to a university building project confirmed that design errors are one of the main causes of significant schedule delays despite construction managers' best efforts to deliver timely completion of the project. The model application confirmed that design errors can be incubated for a long period of time, and identified, in some cases, after construction begins, significantly increasing schedule pressure. Schedule pressure is the latent condition of generating further errors where the negative impact of design errors can be transferred to numerous construction activities, including those that seem not to be directly related with the errors. Finally, the case study proved that construction managers tend to have optimism bias in estimating the recovery of delayed schedules, and this results in underestimation of the negative impacts of hidden design errors and schedule pressure. The developed model was proven to be a more objective and comprehensive tool to assess the impact of hidden errors and schedule pressure. A key expected benefit of the model, therefore, is to assist construction managers in better understanding the dynamics of design errors and more effectively recovering delayed schedules.

This paper strode a meaningful step to better understanding and assessing the impact of design errors. However, further verification is required in order to obtain a general understanding about the mechanism of design errors, and the way in which they can undermine project performance. A method to how we can prevent their negative impact is another finding to be generalized by further verification. The authors are currently analyzing various projects using the developed simulation model. Another research direction of the authors is to estimate the benefit of conducting a constructability review prior to construction, in order to identify hidden errors and complications as early as possible. These works will be reported in papers currently in preparation.

References

[1] M. Park, F. Peña-Mora, Dynamic change management for construction: introducing the change cycle into model-based project management, System Dynamics Review 19 (3) (2003) 213–242.
[2] M.Z.A. Majid, R. McCaffer, Factors of non-excusable delays that influence contractors' performance, Journal of Management in Engineering 14 (3) (1998) 42–49.
[3] A. Touran, P.J. Bolster, S.W. Thayer, Risk Assessment in Fixed Guideway Transit System Construction: Final Report, Northeastern University, January 1994, Prepared for the University Research and Training Program, Federal Transit Administration, 1994.
[4] J.H. Tar, A. Thorpe, R. McCaffer, Contractor project risks contingency allocation using linguistic approximation, Journal of Computing System in Engineering 4 (2–3) (1993) 281–293.
[5] J.D. Sterman, System dynamics modeling for project management. Sloan School of Management, MIT, Last Visit: March, 2011, 1992, http://web.mit.edu/jsterman/www/.
[6] General Accounting Office, Transportation Infrastructure: Cost and Oversight Issues on Major Highway and Bridge Projects. GAO-02-702T, Washington, DC, 2002.
[7] M. Latham, Constructing the Team, HMSO, London, 1994.
[8] F.J. Bromilow, Measurement and scheduling of construction time and cost performance in building industry, The Chartered Builder 10 (1974).
[9] B. Flyvbjerg, N. Bruzelius, W. Rothengatter, Megaprojects and Risk: An Anatomy of Ambition, Cambridge University Press, 2003.
[10] P.E.D. Love, D. Edwards, Forensic project management: the underlying causes of rework in construction projects, Civil and Environmental Engineering Systems 12 (3) (2004) 207–228.
[11] P.E.D. Love, Influence of project type and procurement method on rework costs in building construction projects, Journal of Construction Engineering and Management 128 (1) (2002) 18–29.
[12] P. Barber, D. Sheath, C. Tomkins, A. Graves, The cost of quality failures in major civil engineering projects, International Journal of Quality and Reliability Management 17 (4/5) (2000) 479–492.
[13] S. Han, A hybrid simulation model for understanding and managing non-value adding activities in large-scale design and construction projects, Unpublished Ph.D. Thesis, University of Illinois at Urbana-Champaign, 2008, 2008.
[14] S. Han, S. Lee, F. Peña-Mora, Identification and quantification of non-value adding effort due to errors and changes in design and construction projects, Journal of Construction Engineering and Management (2011), in press (doi:10.1061/(ASCE)CO.1943-7862.0000406).
[15] E. Hagan, G. Mays, Human factors engineering in the US nuclear arena, Nuclear Safety 22 (1981) 337–346.
[16] J.T. Reason, Human Error, Cambridge University Press, Cambridge, 1990.
[17] G. Rounce, Quality, waste, and cost consideration in architectural building design management, International Journal of Project Management 16 (2) (1998) 123–127.
[18] P.E.D. Love, Z. Irani, D. Edwards, Learning to reduce rework in projects: analysis of firms learning and quality practices, Project Management Journal 34 (3) (2003) 13–25.
[19] J.S. Busby, E.J. Hughes, Projects, pathogens, and incubation periods, International Journal of Project Management 22 (2004) 425–434.
[20] K.G. Cooper, The rework cycle: benchmarking for the project manager, Project Management Journal 24 (1) (1993) 17–22.
[21] A. Rodrigues, J. Bowers, The role of system dynamics in project management, International Journal of Project Management 14 (4) (1996) 213–220.

[22] A. Rodrigues, T. Williams, System dynamics in project management: assessing the impacts of client behavior on project performance, Journal of Operation Research Society 49 (1) (1998) 2–15.
[23] P.E.D. Love, D.J. Edwards, S. Han, Y.M. Goh, Design error reduction: toward the effective utilization of building information modeling, Research in Engineering Design 22 (3) (2011) 173–187. doi:10.1007/s00163-011-0105-x.
[24] E.W.K. Tsang, S.A. Zahra, Organizational unlearning, Human Relations 61 (10) (2008) 1435–1462.
[25] P.E.D. Love, D.J. Edwards, Z. Irani, D.H.T. Walker, Project pathogens: the anatomy of omission errors in construction and resource engineering projects, IEEE Transactions on Engineering Management 56 (3) (2009) 425–435.
[26] J.T. Reason, A. Hobbs, Managing Maintenance Error: A Practical Guide, Ashgate Publishing Company, 2003.
[27] J.S. Busby, Error and distributed cognition in design, Design Studies 22 (2001) 233–254.
[28] P.E.D. Love, D.J. Edwards, Z. Irani, Forensic project management: an exploratory examination of the causal behaviour of design-induced error, IEEE Transactions in Engineering Management 55 (2) (2008) 234–248.
[29] P.E.D. Love, R. Lopez, D.J. Edwards, Y. Goh, Error begat error: design error analysis and prevention in social infrastructure projects, Accident Analysis and Prevention (2011), in press (doi:10.1016/j.aap.2011.02.027).
[30] A. Robinson-Fayek, M. Manjula Dissanayake, O. Campero, Measuring and classifying construction rework: a pilot study, Department of Civil and Environmental Engineering, Construction Owners Association of Alberta, Alberta, Canada, 2003.
[31] J.L. Burati, J.J. Farrington, W.B. Ledbetter, Causes of quality deviations in design and construction, Journal of Construction Engineering and Management 118 (1) (1992) 34–49.
[32] S. McConnell, Brooks' law repealed, IEEE Software 16 (6) (1999) 6–8.
[33] D.R. Friedrich, J.P. Daly, W.G. Dick, Revisions, repairs, and rework on large projects, Journal of Construction Engineering and Management 113 (3) (1987) 488–500.
[34] M.E. Paté-Cornell, Organizational aspects of engineering system reliability: the case of offshore platforms, Science 250 (1990) 1210–1217.
[35] L. Koskela, Application of the new production philosophy to construction, Technical Report No. 72, CIFE, Stanford University, 1992.
[36] T. Williams, Modelling Complex Projects, John Wiley & Sons, New York, NY, 2002.
[37] F. Peña-Mora, S. Han, S. Lee, M. Park, Strategic-operational construction management: a hybrid system dynamics and discrete event approach, Journal of Construction Engineering and Management 134 (9) (2008) 701–710.
[38] S. Lee, S. Han, F. Peña-Mora, Integrating construction operation and context in large-scale construction using hybrid computer simulation, Journal of Computing in Civil Engineering 23 (2) (2009) 75–83.
[39] S. Han, M. Park, Interactive parade game: impact of managerial reactions to workflow variability, ITCon 16 (2011) 105–118.
[40] R. Newbold, Project Management in the Fast Lane: Applying Theory of Constraints, CRC Press L.L.C., 1998.
[41] M. Lee, A.S. Hanna, W. Loh, Decision tree approach to classify and quantify cumulative impact of change orders on productivity, Journal of Computing in Civil Engineering 18 (2) (2004) 132–144.
[42] K. Cooper, Naval ship production: a claim settled and a framework built, Interface 10 (6) (1980) 20–36.
[43] G. Richardson, A.L. Pugh, Introduction to System Dynamics Modeling with Dynamo, MIT Press, Cambridge, MA, 1981.
[44] T. Abdel-Hamid, The dynamics of software development project management: an integrative system dynamics perspective, Ph.D. Dissertation, Sloan School of Management, MIT, Cambridge, MA, 1984.
[45] D. Ford, J. Sterman, Dynamic modeling of product development processes, System Dynamics Review 14 (1) (1998) 31–68.
[46] J. Lyneis, K. Cooper, S. Els, Strategic management of complex projects: a case study using system dynamics, System Dynamics Review 17 (3) (2001) 237–260.
[47] S. Lee, F. Peña-Mora, M. Park, Quality and change management model for large scale concurrent design and construction projects, Journal of Construction Engineering and Management 131 (8) (2005) 890–902.
[48] M. Park, W. Kim, H. Lee, S. Han, Supply chain management model for ready mixed concrete, Automation in Construction 20 (1) (2011) 44–55.
[49] J.C. Martinez, Methodology for conducting discrete-event simulation studies in construction engineering and management, Journal of Construction Engineering and Management 136 (1) (2010) 3–16.
[50] R.J. Chapman, The role of system dynamics in understanding the impact of changes to key project personnel on design production within construction projects, International Journal of Project Management 16 (4) (1998) 235–247.