Case Study

Optimization of Change Order Management Process with Object-Oriented Discrete Event Simulation: Case Study

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Abstract: Change orders are common to most construction projects. They can significantly increase project cost and duration, leading to more claims and disputes and ultimately creating an adversarial relationship among project members. Evidence has shown that a contributing factor to the inefficiency of change order management is the management process utilized in most construction projects, which always relates to suboptimal allocation of resources and unnecessary procedures. Discrete event simulation (DES) provides an effective approach to streamline the change order management process by evaluating a series of improvement options. Based on a comparison of two prevailing DES paradigms, activity scanning (AS) and process interaction (PI), this paper presents an object-oriented DES model to investigate the change order management process. A case study has been performed to investigate the change order management process at a Midwestern land-grant university with the proposed simulation model, where the bottlenecks of *as-is* process have been identified and improved. The developed model employs PI paradigm rather than AS paradigm because the former is capable of capturing the real time state changes of change orders. Sensitivity analysis (SA) is also applied to examine the quantitative impacts of changeable variables to evaluate improvement options. The results indicate that PI paradigm outperforms AS in the investigation of change order management process. It is also expected that the developed model provides an optimization tool to support change order management. **DOI: 10.1061/(ASCE)CO.1943-7862.0001092.**

Author keywords: Change order; Process interaction; Activity scanning; Discrete event simulation; Object-oriented programming; Sensitivity analysis; Quantitative methods.

Introduction

A project change order, defined as a work "that results in a modification of the original scope, execution time, or cost of work," is common to most construction projects (Camlic et al. 2002). Many of performance problems in construction projects are associated with change orders, including decreased productivity (Moselhi et al. 2005), project delays (Alnuaimi et al. 2010), and cost overruns (Serag et al. 2010). In a construction project, change orders always lead to increased frequency of planning, increased project management and supervision need, overmanning, schedule compression, out-of-sequence work, and lack of availability of resources to meet the requirements of the changes (Hanna et al. 1999). It is also very difficult to determine proper compensation for the parties involved, which causes disputes, and ultimately contributes to the adversary relationship among construction stakeholders (Chen 2008).

In addition to the efforts to avoid changes in construction projects, the research community has also highlighted the importance of better change order management because it is expected to mitigate the negative impacts of changes. For example, Karim and Adeli (1999) developed an object-oriented change management system to continually monitor, analyze, and approve change orders. The developed system enables intelligent decision making that expedites the change order process. Park and Pena-Mora (2003) tested a model-based change management system to analyze change impact on project performance according to change characteristics, discovery status, and time. The system was incorporated into a cohesive dynamic project model to enhance project performance in the real world by providing effective management plans and policy guidelines. Other representative works in change order management methods and systems include those done by Love et al. (2002), Chan and Leung (2004), and Chen (2008).

However, there still lacks an effective approach for optimizing the management process of change orders. Efforts have been made to develop advanced management or decision support systems to expedite the communication and data exchange of change orders (Charoenngam et al. 2003), whereas it helps little to identify the inefficient steps in the change order management process. On the other hand, for those who are interested in eliminating inefficient steps in change order management, subjective knowledge, such as domain experiences, interviews to stakeholders, and brainstorms, is often preferred (Loch and Terwiesch 1999; Mechanda 2005), which probably leads to suboptimal solutions while suppressing the real optimal ones.

Inspired by the work done by Han et al. (2011), this paper aims to explore the applicability of discrete event simulation (DES) in optimizing the change order management process. As a popular simulation approach, DES has been widely used to investigate the behavior of complex systems in the area of construction engineering and management, such as construction operations (Martinez 2010), but its application in change order management is limited. Several questions remain unanswered regarding the use of DES in tackling the problems associated with the optimization

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of change order management process. Particularly, the popular DES paradigm used in typical construction problems [i.e., activity scanning (AS)] could be problematic when used to study change order management process. The AS focuses on identifying the various construction activities and the conditions under which they take place (Martinez and Ioannou 1999), which can be inefficient in capturing the dynamic status updates of change orders. In addition, new clinical evidence is needed to testify the applicability of DES in addressing change order management problems. Thus this paper will answer the following two questions:

1. Objective 1: How can DES be used to support dynamic decision-making for a better change order management process?
2. Objective 2: What is the best DES paradigm to realize Objective 1?

Based on a comparison of prevailing DES paradigms, this paper presents an object-oriented DES model based on process interaction (PI) to optimize change order management process. A case study has been performed to investigate the change order management process at Michigan State University with the developed simulation model, where the bottlenecks of as-is process have been identified and improved. The remainder of the paper introduces the findings.

Background

Change Order Management

In recognition of the importance of change orders in construction projects, a growing body of literature has started to investigate the roles and implications of change order management. As an integral part of construction project management, the management of change orders refers to the procedure for requesting, verifying, and approving a change through written documents to add, delete, or modify the work on a construction project (Yelakanti 2005). Efforts have been made to explore the root reasons of change orders to reduce the need of issuing new change orders (Hsieh et al. 2004; Lee et al. 2006; Terwiesch and Loch 1999; Wu et al. 2004) and investigating the influences of change orders so that negative impacts can be mitigated (Cox 1997; Hanna et al. 1999; Leonard 1988; Moselhi et al. 2005; O'Brien 1998). Recently, scholars have also started to investigate the management process of change orders (Charoenngam et al. 2003; Ibbs et al. 2001; Shipton et al. 2014). It was found that a contributing factor to the inefficiency of change order management is the suboptimal allocation of resources and unnecessary procedures related to a defectively organized management process. For example, Loch and Terwiesch (1999) found that the complex approval process and congestion effects (caused by demands beyond the management capacity) greatly contribute to the long response time of many change orders, leading to longer construction time and increased costs. Therefore, streamlining the change order management process can help reduce the time and cost of processing change orders (Loch and Terwiesch 1999).

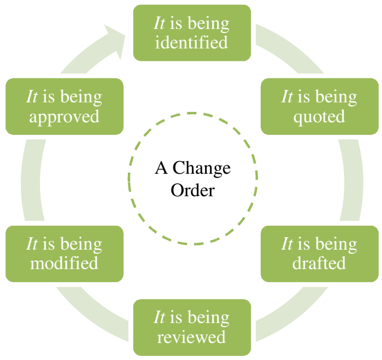
This change order management process could be time consuming and costly if it is not well-organized and streamlined. Given the increased complexity and stricter management requirements of modern construction projects, change order management usually requires longer processing time and higher management cost than anticipated (Alnuaimi et al. 2010). For example, in a previous case study at a university, it was found that the average processing time of a change order was 205 days. Approximately 10% of the increased project cost was caused by change order processing (Mrozowski 2004). Management resources, such as the committed time of engineers and architects, are not always efficiently allocated to maximize the workflow (Yelakanti 2005). Critical decisions, such as the number of cost items included in an official change order, are often arbitrarily made (Yelakanti 2005). Streamlining the change order management process is expected to significantly improve the time and cost performance of construction projects (Mechanda 2005).

A variety of models have been developed to improve the change order management process. Karim and Adeli (1999) developed a change order management system, CONSCOM, to tackle problems of highway construction change order management. CONSCOM can be used as an intelligent decision support system for owners to review schedules, monitor progress, and conduct cost-time trade-off analysis for change order approval. Ibbs et al. (2001) proposed a five-step project change management paradigm to minimize deleterious changes by continuously improving beneficial changes from lessons learned. Following Ibbs et al., Lee et al. (2005) developed a system dynamics model called dynamic planning methodology (DPM) to evaluate negative impacts of changes on construction performance and to reduce the detrimental impacts of change orders before any decision is made. Zhao et al. (2010) developed a change prediction model using activity-based dependency structure matrix (DSM) to facilitate change management, wherein Monte Carlo simulation is applied to quantify the probability of changes to any activity in a construction project and to make specific mitigation recommendations to the decision makers.

A recent work reported by Han et al. (2011) inspires the use of DES to tackle this problem. Although not specifically aiming to improve the efficiency of change order management, Han and colleagues utilize DES to identify nonvalue added efforts (NVAE) in construction projects. Combined with system dynamics (SD), their model is expected to be able to quantify NVAE triggered by changes and capture the propagation of NVAE between interrelated activities. Han and colleagues' DES model provides a potential solution to dynamically optimize the change order management process but still focuses on the implications of change orders. Following their work, this paper reviews the features of DES as a candidate tool for the optimization of change order management process.

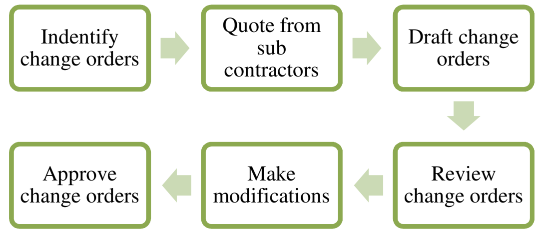
Discrete Event Simulation

The DES models a system as a chronological sequence of events where each event can be defined as an instant of time at which a significant state change occurs in the system (Robinson 2004). As commented by Martinez, the overwhelming majority of simulation studies in the construction area is about the use of DES for quantitative analysis of construction operations and processes (Martinez 2010). It has been used to tackle a wide range of problems, including project planning (AbouRizk and Wales 1997; Lee and Arditi 2006), optimization of construction operations (Hassan and Gruber 2008; Marzouk 2004; Zayed and Halpin 2001; Zhang et al. 2006), resource allocation (Martinez et al. 2001; Zhang et al. 2008, 2007), and strategic construction management (Han et al. 2011; Peña-Mora et al. 2008). For example, Zayed and Halpin (2001) investigated concrete batch plant operations and analyzed alternative solutions of resource management using DES. Martinez et al. (2001) utilized DES to optimize resource allocation in air-side airport operations. Peña-Mora et al. (2008) developed a hybrid model of DES and SD to integrate the decisions on strategic perspective and operational details for a better project performance. Existing studies indicate DES's potential to identify bottlenecks in the process, reveal inefficient operational activities, examine the alternatives, and ultimately improve the productivity. Evidence has also shown that DES could be an alternative to analytical approaches for a more practical analysis of construction problems (Zhang et al. 2008). The process of attempting to build a DES model forces the



[Pseudo code]
start (initialize parameters including conditions)
for (*i* in 1..*number of entities*) {
    create entity$_i$
    if (the i^{th} condition is true){
        execute entity$_i$.lifeCycle
    } **else** {
        wait
}
end

(a)



[Pseudo code]
start (initialize parameters including conditions)
for (*i* in 1..*number of activities*) {
    if (the i^{th} condition is true){
        execute activity$_i$
    } **else** {
        wait
}
end

(b)

Fig. 1. Worldview of process interaction and activity scanning: (a) the worldview of process interaction; (b) the worldview of activity scanning

engineers to "think about a problem in ways that lead to its solution" (Martinez 2010).

Building on Hooper's (1986) work, Martinez and Ioannou (1999) categorized DES models into two general paradigms, including AS and PI. They further suggested that AS is more suitable for construction simulation because it captures the complexity of interacting resources and rich states (Martinez and Ioannou 1999). As a result, popular DES tools in the construction area are mostly based on AS or similar simulation paradigms, including CYCLONE (Halpin 1977), Stroboscope (Martinez 1996), and Ezstrobe (Martínez 1998). However, discussed subsequently, this paper finds that AS-based DES tools can hardly meet the need of studying change order management process. It requires a reevaluation of DES paradigms in this subject.

Comparison of Two Major DES Paradigms

A PI-based DES model is built from the standpoint of the entities that flow through the system (Martinez and Ioannou 1999). These entities, also referred to customer entities, pass through a sequence of activities in a system, interact with the resources at each activity for certain duration, and then exit the system (Lu 2003). For example, in a change order management process model, an entity is a change order. Once a change order entity is created, it flows to different actors to be quoted, drafted, reviewed, modified, reviewed, and approved when certain conditions are met [Fig. 1(a)]. In this process, the *attributes* of the change order, such as the approval status and size, will be altered. As addressed by Hooper (1986), PI strategy is particularly suited to modeling operations where the customer entities are distinguished by many attributes, whereas the resources that serve these entities are less important with few attributes and a limited number of states. As a result, most operations in manufacturing and the industrial and service industries are of this type (Martinez and Ioannou 1999).

In contrast, an AS-based DES model is built from the standpoint of activities that are performed in a system (Martinez and Ioannou 1999). Taking the same example of change order management process, the activities that can be modeled include identifying, quoting, drafting, reviewing, modifying, and approving change orders when the time schedule and conditions are met [Fig. 1(b)]. When the change order management process is modeled with AS paradigm, entities (i.e., change orders) and their attributes are not important; instead, the key is to identify the activities and the conditions under which they take place. During the simulation, a global time control procedure scans activities in priority order for time eligibility and other activation conditions and orderly executes the activities in which activation conditions are met (Hooper 1986). The rationale of using AS paradigm is that for certain problems, a variety of resources with distinct properties must collaborate because of the scarcity. It is suggested that AS is a more suitable simulation paradigm for construction problems because "most construction operations include many interacting resources that can be in numerous states and where logical complexities are best described in terms of the conditions required to carry out activities" (Martinez and Ioannou 1999).

Fig. 1(a) illustrates the PI paradigm where each change order is modeled as an object. The simulation is executed to change the status of the change orders according to the conditions. As shown in the pseudo code, after initialization, a change order is identified. Then, the condition is evaluated, and according to the condition, a certain action is taken to change the status of the change order. For example, for an identified change order, the condition is *it needs approval*; accordingly, the approving process is activated and the status of the change order is changed to *approved*. In contrast, the AS paradigm models the process as a chain of activities [Fig. 1(b)]. Each activity takes a certain amount of time and requires certain resources. For example, the change order management process includes: identifying change orders, quoting from subcontractors, drafting change orders, reviewing change orders, making modifications, and approving change orders. The AS does not model change orders but only the time and resources needed to process change orders.

After comparing the differences between PI and AS, this paper decides to apply PI to investigate the change order management process. A change order has multiple states, such as being drafted, being reviewed, and being approved, and a variety of attributes, such as size and dollar value. These states and attributes determine the next-step procedure in the process, affecting the duration of activities. Capturing the state and attribute changes is of the central interest for analysis. For example, a change order usually contains one or more items, and the items may vary in dollar values. It is expected that the number of items and total dollar value of a change order significantly affect the time needed to process it and may lead to completely different management procedures (Mechanda 2005). Nevertheless in an AS-based DES model, all the change orders are treated as identical, the processing time of each activity is simply generated from a probability distribution (often obtained from work sampling and follow-up statistical analysis), and the divergence between two procedures (for example sending the change order for vice president review versus approving the change order), if any, are modeled as a pure probability. The AS paradigm disconnects the relationship between a change order's attributes and the corresponding actions (and outcomes). In contrast, in a PI-based DES model, when a change order is sent to an actor (often modeled as an agent), the actor will read the critical attributes (e.g., the size and dollar value) of the change order, and adopt proper actions, which, in turn, lead to different outcomes. Therefore, the connection between the attributes of a change order and the proper actions is captured.

Another reason to apply PI in the change order management process studies roots from the need of recording simulation results. An AS-based DES model usually documents simulation results on the basis of activities, i.e., storing information in each activity object. For example, the drafting duration of each change order is added sequentially in the activity object called *drafting change orders*. After all the simulation experiments are completed, a statistical fit may ultimately reveal that it takes five days for drafting a change order on average, with a standard deviation of one day. This aggregated analysis helps researchers examine the performance of the process as a whole, but it is difficult to obtain the specific duration for drafting a given change order. The AS-based DES model does not track the difference between two change orders. In a PI-based DES model, in contrast, a researcher can easily create a space in each change order object to document critical time points when its state changes. Information is encapsulated in each change order, and it is easier to distinguish the outcomes of different change orders. When the purpose is to investigate the management process of change orders, it is obvious that the state change of each change order is more important than the information about activities and resources. Input and output data should be embedded and stored in each of the customer entities, i.e., change orders, to enable in-depth analysis. The PI paradigm provides a worldview that centers on the simulated customer entities and thus, is more suited to change order process modeling. Another benefit of the PI paradigm is the ease to coordinate with object-oriented programming (OOP), a programming paradigm where data and their methods are encapsulated in a set of subprograms, called classes. To store or read data, one can simply instantiate a class to retrieve relevant attributes. This paper utilizes an OOP-based simulation platform, Anylogic (2015), to develop a PI-based OOP DES model on change order processing. For more information about Anylogic, please refer to the appendix.

Simulation Model for Change Order Management Process Optimization

On the basis of PI paradigm, an OOP-based DES model has been developed to optimize the management process of change orders. Fig. 2 illustrates the execution process of the developed model.

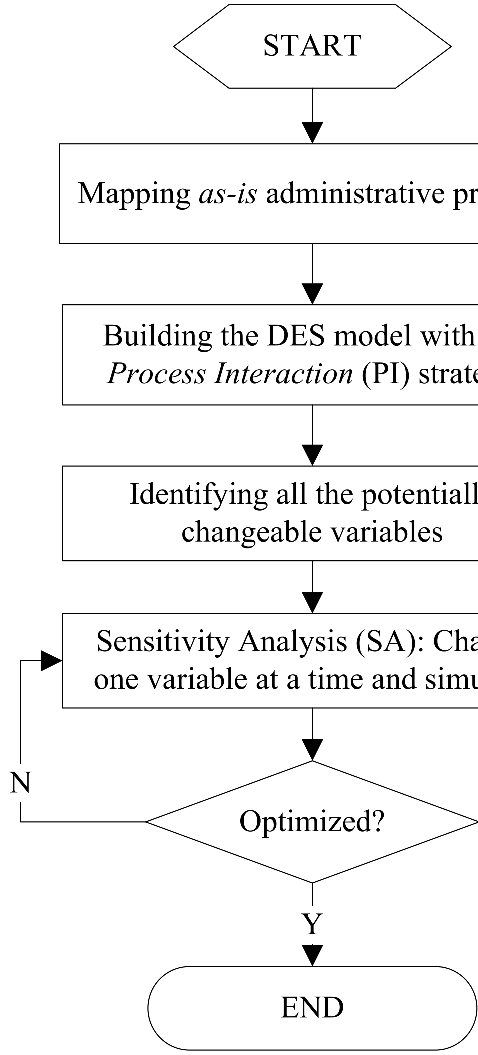


Fig. 2. Execution process of the developed model

The execution of the model can be described in the following steps:

1. Mapping as-is management process: The first step is to map the present change order management process, denoted as as-is process. A case study has been conducted to simulate the change order management process at a Midwestern land-grant university. In the as-is process mapping, the change order management process of engineering and architectural service (EAS) projects (a project type at the studied university) was selected because these projects generally have complex change order processes that can hardly be optimized based on experience. The as-is process map constitutes the foundation of the DES model development.
2. Developing a DES model based on PI paradigm: Based on the mapped management process and collected data (e.g., processing time), a DES model can be built based on the PI paradigm. In the case study, a set of DES models were built to simulate the change order management process.
3. Identifying potential improvements: The potential options to improve the as-is management process are identified on the basis of interviews to the stakeholders. In the case study, the possible improvements were relevant to the resource reallocation

(e.g., the number of architects and engineers assigned to review change orders), the batch size of the change orders (i.e., number of change items included in a change order), and alternative processes.
4. Optimizing the change order management process based on sensitivity analysis (SA). The SA is an approach to examine how different inputs of a model quantitatively affect variation in the output of a model (Cruz 1973). By systematically changing parameters in a model, the effects can be calculated. After DES simulation results are obtained, a set of SA were conducted to examine the relative importance of proposed improvements.In the simulation, the value of each control variable is changed from the minimum to the maximum in sequence to scan over the entire uncertain space. Then the results are recorded to find out the optimal solution. In the case study, the SA results were mainly demonstrated graphically, and at the end of analysis, a set of recommendations were made to accelerate change order management process at the university.
5. Evaluating the improved change order management process. Finally, the results of SA and DES simulation will be integrated into an improved management process. Then, the second DES model is built to analyze the new process and to compare the key performance indicators over the previous process (as-is process). In the case study, the key performance indicators include the average processing time per change order.

More details about the case study are introduced in the remainder of this paper.

Case Study

The case study was based on 130 change order data of 19 construction projects at the studied university (Mechanda 2005). In the following sections, the change order management process at the studied university is described. Then, a set of DES models are developed to analyze the improvement options.

Mapping As-Is Management Process of Change Order Management

Based on the interviews with the engineers and contractors at the studied university, the as-is process map of the change order management process has been developed, as illustrated in Fig. 3. The process starts with identifying potential cost items that might need changes (called change items) through requests for information (RFIs) and meeting minutes. Then, the owner's construction representatives (CRs) seek inputs from in-house and/or outside consultants on more details about the change items. Afterward, the need for changes are reviewed and evaluated by architects and engineers (AEs). If the need is confirmed, AEs group (or batches) a number of items to prepare a potential change order. The length of this assembly time and number of items included in a change order are not standardized and are often left to the discretion of CRs. Although the requests may be made through informal quotes at this point, more often, a formal request for quote is sent to the general contractor (GC). The GC then requires quotes from subcontractors (subs). This process may take up to two weeks at the university. Negotiations may occur in certain cases, which typically take one week. After the final agreement is achieved, a final change order is drafted and authorized by AEs. The date when the change order has been officially prepared is documented as *Change order Date* in the system. Then, the architect prepares three copies of the change order and sends them to the GC. The GC, after receiving the copies of change order, signs all of them and returns two of them to the university. The GC authorization step may be skipped if the projects are designed in-house. Then the university's design administrators (admins) and university engineers (engineers) at the university sign on the change order, respectively, and send it to contract and grant management (CGA) at the university. The CGA will examine and verify the changes. If the changes need more clarification or modifications, the CGA will make the corrections or return the change order to the architect for further processing. After verification, a CGA staff member enters the change order information into the university information system, FAMIS. After the change order shows in FAMIS, the vice president of the university (VP) approves the change order, which is indicated by the *Authorization Date* in the system. Finally, the university staff members finalize the change order and send it to *Physical Plant* (the department responsible for all construction and maintenance projects at the university) and the GC. According to the historical data, the entire process takes 205 days on average at the university; in particular, it takes 140 days to initialize a change order, i.e., from identifying change items to the architect drafting the change order. In contrast, it only takes four and five days on average for the architect and GC to authorize the change order, respectively.

Developing a PI-Based DES Model

Anylogic 7.1 was used to build a PI-based DES model for the as-is change order management process at the university (AnyLogic 2015). Fig. 4 illustrates the developed model. For more information about the symbol meanings, please refer to appendix.

According to the data of 130 change orders, the processing time of each step follows a normal distribution:

$$T_i \sim N(\mu_i, \sigma_i^2) \quad (1)$$

where T_i = processing time for the ith step; and μ_i and σ_i = mean and standard deviation, respectively. A statistical analysis (Mechanda 2005) revealed that for a given change order, there is a linear relationship ($R^2 = 0.5$) between the average processing time μ_i and the number of change items included in the change order (batch size), which is

$$\mu_i = a_i \times \beta_j + b_i \quad (2)$$

where β_j = number of change items included in the jth change order; and a_i and b_i = parameters of the ith processing step. Building on Eqs. (1) and (2), the processing time of a particular change order at each step can be generated in the simulation. Specific parameter values are shown in Table 1 based on the collected data.

In order to perform in-depth statistical analysis, the values of certain change order attributes need to be recorded dynamically, including batch size, dollar value, and the duration for which a change order stays in the system (from identification to approval). The PI paradigm makes it easier. Change orders and relevant items are modeled as objects of classes, with their attributes embedded in the class code. The sample code is shown in Appendix II.

The time points collected in the simulation can be used to calculate the time spans. For example, the total time for processing a change order can be calculated as follows:

$$TT_i = \text{order}_i \cdot \text{approved} - \min(\forall \text{item}_i \cdot \text{entered System}) \quad (3)$$

where TT_i = total processing time for the ith change order; it is equal to the span from when the first change item has been identified to the point when the change order has been approved. Similarly, other time spans for a particular change order can be calculated, such as how long it takes to initialize a change order, i.e., from items identified to the change order drafted.

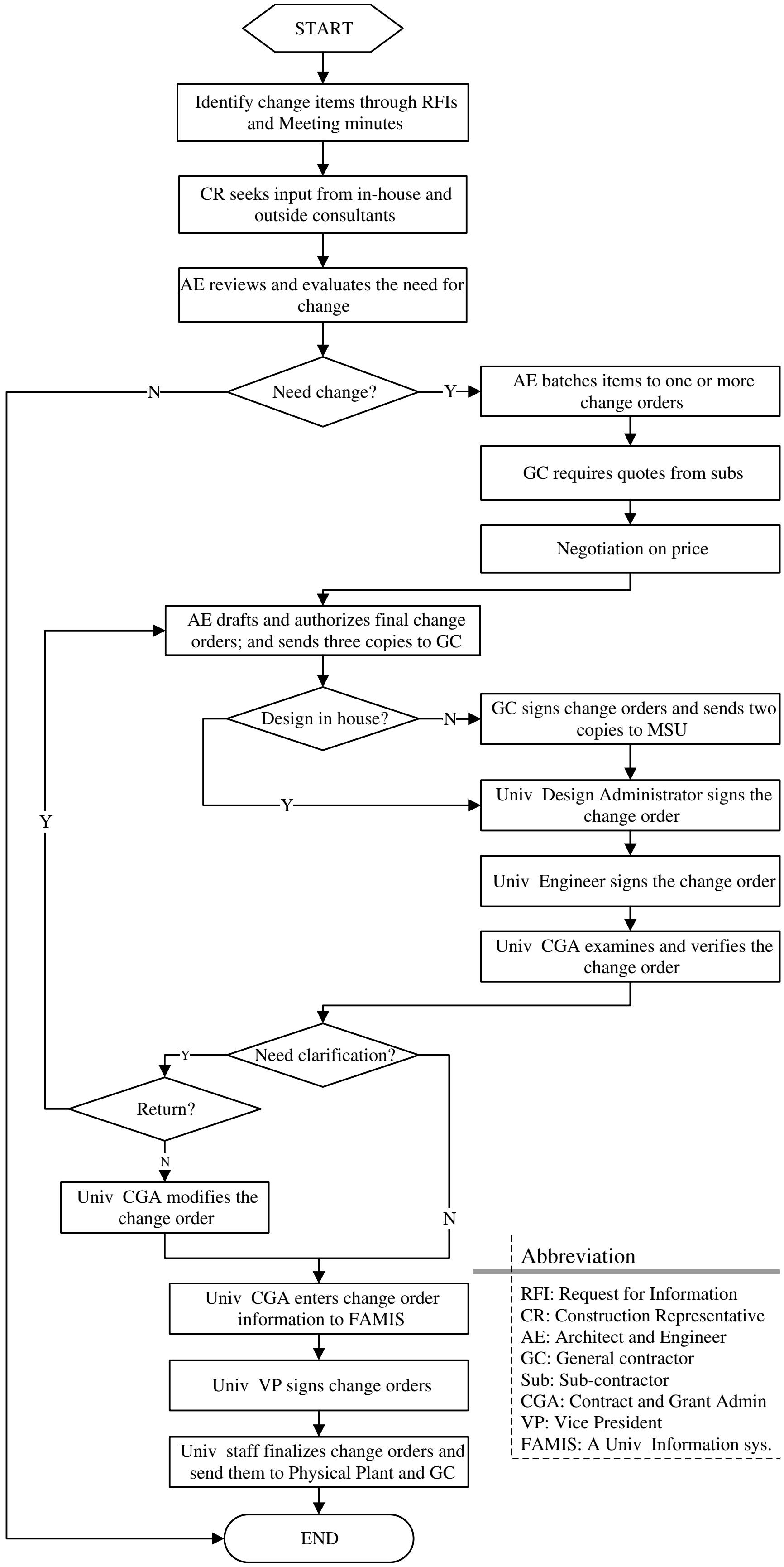


Fig. 3. Workflow of as-is change order management process at the studied university

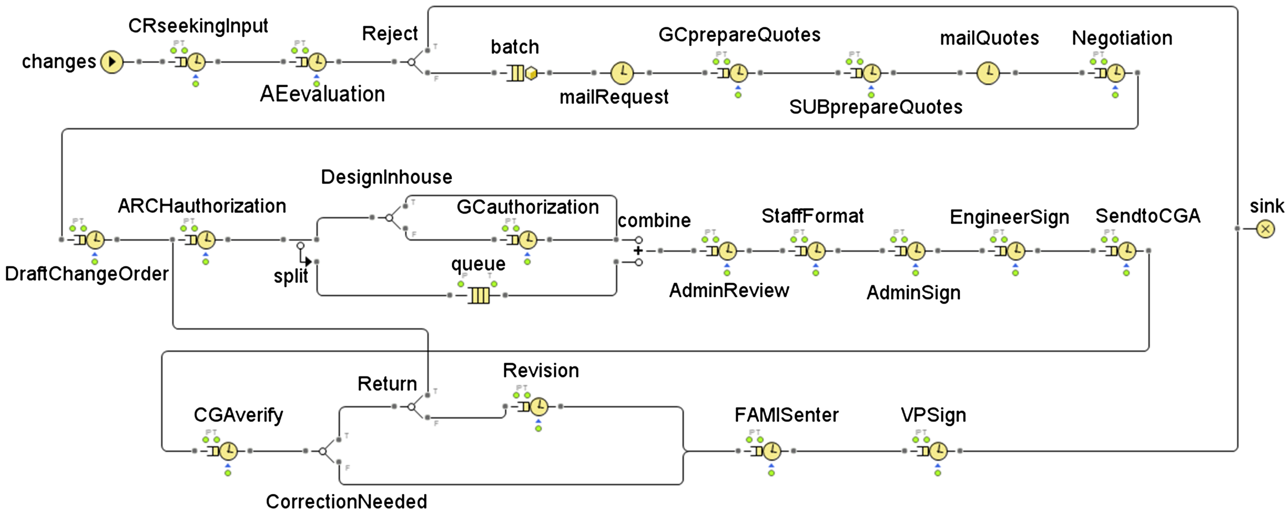


Fig. 4. DES model for the as-is change order management process

Table 1. Activities and Distribution Parameters

Activities or inputs	Description	(a, b, σ)
CRseekingInput	Construction representative seeks inputs from in-house or outside consultants	(0.96, 7.5, 9.4)
AEevaluation	Architects and engineers evaluate changes	(1.28, 10, 16.7)
batch	Group several change items into a single change order	N/A
mailRequest	The change requests are sent to general contractor	(0.45, 3.5, 2.0)
GCprepareQuotes	General contractor prepares quotes	(0.96, 7.5, 9.4)
SUBprepareQuotes	Subcontractors prepare quotes	(0.96, 7.5, 9.4)
mailQuotes	General contractor sends the quotes back	(0.45, 3.5, 2.0)
Negotiation	Owner and general contractor negotiate on the price of changes	(0.38, 3.0, 1.5)
draftChangeOrder	Architects and engineers draft the official change order	(0.32, 2.5, 1.0)
AEauthorization	Architects and engineers authorize the official change order	(0.26, 8.0, 18.7)
GCauthorization	General contractor authorizes the official change order	(0.26, 4.5, 5.8)
AdminReview	University design administrator reviews the change order	(0.58, 4.5, 3.4)
StaffFormat	A university CGA staff member formats the change order	(0.19, 1.5, 0.4)
AdminSign	University design administrator signs the change order	(0.35, 2.8, 1.3)
EngineerSign	University engineer signs the change order	(0.35, 2.8, 1.3)
SendtoCGA	The signed change order is sent back to university CGA	(0.13, 1.0, 0.2)
CGAverify	University CGA verifies the signed change order	(0.78, 6.0, 6.0)
Revision	University CGA revises the change order when errors were found	(1.7, 13.0, 28.2)
FAMISenter	A university CGA staff member enters the change order information into FAMIS (university information system)	(0.38, 3.0, 1.5)
VPsign	The vice president of the university also needs to sign the change order	(1.8, 14, 32.7)
FinalizeandMail	University CGA finalizes the change order and send it to university's physical plant and general contractor	(0.45, 3.5, 2.0)
Item dollar value	The dollar value of each change item	Triangular (0,500,10000)
Batch size	The number of items included in each change order	—

The validation and calibration were performed in two ways, including input validation and output validation. For input validation, historical data has been collected to fit probability distributions of critical variables, including the number of change items included in the change order and the durations of processing change orders. Then, the simulated change order processing time was compared with the actual distribution of processing time. A Chi-squared test confirmed that the simulated duration and the actual duration of change order processing come from the same distribution ($p < 0.05$).

Identifying Potential Improvements

Potential improvements are the changeable factors expected to influence the change order management process. By examining all the potential factors in the as-is process, three factors can be changed to improve the change order management process at the studied university:

- Batch size: At the university, there were no explicit rules on the proper number of change items included in a change order. Because batch size affects the average time taken for processing a change order [Eq. (2)], it is expected that there is an optimal level of batch size that leads to the biggest productivity.
- Particular activities: Several activities were taking too long and clearly were the bottlenecks of the entire process. These activities should be accelerated according to the order of priority.
- Approval process: In order to ensure the quality of change order management, many approval layers have been set. However, clearly certain change orders have a relatively small dollar value that will not need as complex procedures as those with a bigger

dollar value. The process should be reengineered to reduce the processing time while maintaining the quality.

Except for the three changeable factors listed previously, some other factors, although influential, are, in general, out of control. For example, the frequency and dollar value of a change item mainly depends on the actual needs of the project and can hardly be optimized. This is consistent with the findings of interviews with university engineers, designers, and contractors (Mechanda 2005). Based on further brainstorming, Mechanda also made recommendations on improving the three changeable factors. This paper revisits the previous conclusions and compares them to the findings of a sensitivity analysis. On the basis of the developed DES model, a set of sensitivity analysis experiments were performed to investigate the following three questions:

1. What is the optimal batch size?
2. What activities should be done faster?
3. How should the as-is process be reengineered?

The following section introduces the simulation findings.

Simulation Results and Analysis

What is the Optimal Batch Size?

Once the change items have been evaluated and verified, AEs batch a particular number of change items into a single change order. A bigger sized change order requires longer time to process, but once it has been approved, more change items are processed at once. In contrast, a smaller sized change order demands shorter time to process, but fewer change items would be finished at one time. There is a trade-off between the time for processing a change order and the number of change items it contains. Mechanda (2005) suggested that ten items in one change order was optimal for university projects, according to the findings of a brainstorm session. This conclusion has been reexamined on the basis of the productivity, i.e., the number of items processed per time unit (day)

$$P = \frac{\sum_{i=1}^{n} \beta_i}{TT} \tag{4}$$

where P = productivity; β_i = number of items contained in the ith change order; n = total number of change orders; and TT = duration of the project (days). This study performed 30 experiments to examine the productivity of change order processing under different level of batch sizes (Fig. 5). As shown, the optimal batch size is approximately 18, which leads to better productivity. It suggests that the findings of the brainstorm session might not be optimal.

Besides the overall productivity, the reliability of workflow is also a key to the change order processing. Therefore, absolute deviation of processing time per change order under different level of batch sizes has also been examined (Fig. 6). Bigger absolute deviation pertains to bigger level of volatility of processing time, which, in turn, makes the performance more unpredictable. Therefore, the batch size should be designed to minimize absolute deviation. When the batch size is relatively big, there are fewer change orders because more change items are batched in to a single change order, and thus, there are no sufficient samples on which to perform statistical analysis. As a result, the average values of 30 repeated experiments were used to compare the deviations (the thicker line in Fig. 6). It shows that the deviations of batch sizes 3 through 17 are relatively short (less than 13 days).

Taking into account both the productivity and the reliability of the workflow, a batch size level of 15 is more preferable. This number is bigger than the recommendation made in the brainstorm session (Mechanda 2005).

What Activities Should Be Done Faster?

Mechanda (2005) suggested that a time goal should be set for the processing activities in order to reduce the total time for change order management. This paper finds that activities have different levels of utilization and therefore should be fully examined to identify the real bottlenecks. The utilization of an activity is defined as

$$U = \frac{\sum_{i=1}^{TT} W_i}{TT} = \frac{\sum_{i=1}^{TT} W_i}{\sum_{i=1}^{n} (W_i + I_i)} \tag{5}$$

where U = unitization of an activity; TT = project duration in days; and W_i and I_i = two state indicators on the ith day. If the activity is active on the ith day, W_i equals to 1; if it is idle, I_i equals to 1; otherwise, they both equal 0. Therefore, $U = 1$ refers to 100% utilization, and $U = 0$ means 0% utilization. According to Eq. (5), the utilizations of all the activities under different batch sizes (1 through 15) were simulated. Results are illustrated in Fig. 7.

Per the definition, if an activity has a higher utilization level, it is busier. Given the linearity of the entire management process, an activity with a higher utilization level can be interpreted as a bottleneck in the process because it means that work tends to congest in

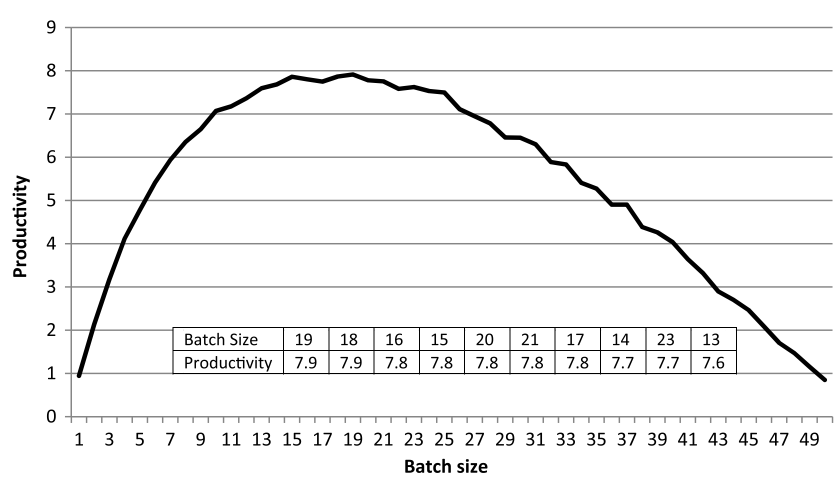


Fig. 5. Productivity of change order processing under different batch sizes (30 repeated experiments)

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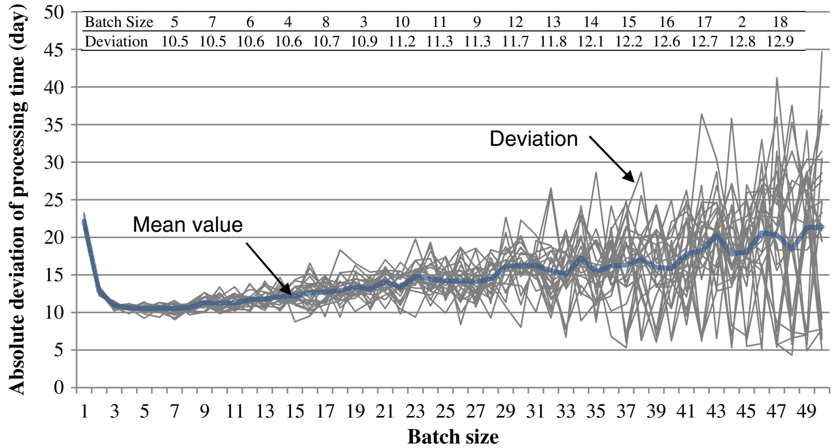


Fig. 6. Absolute deviation of processing time per change order under different batch sizes (30 repeated experiments)

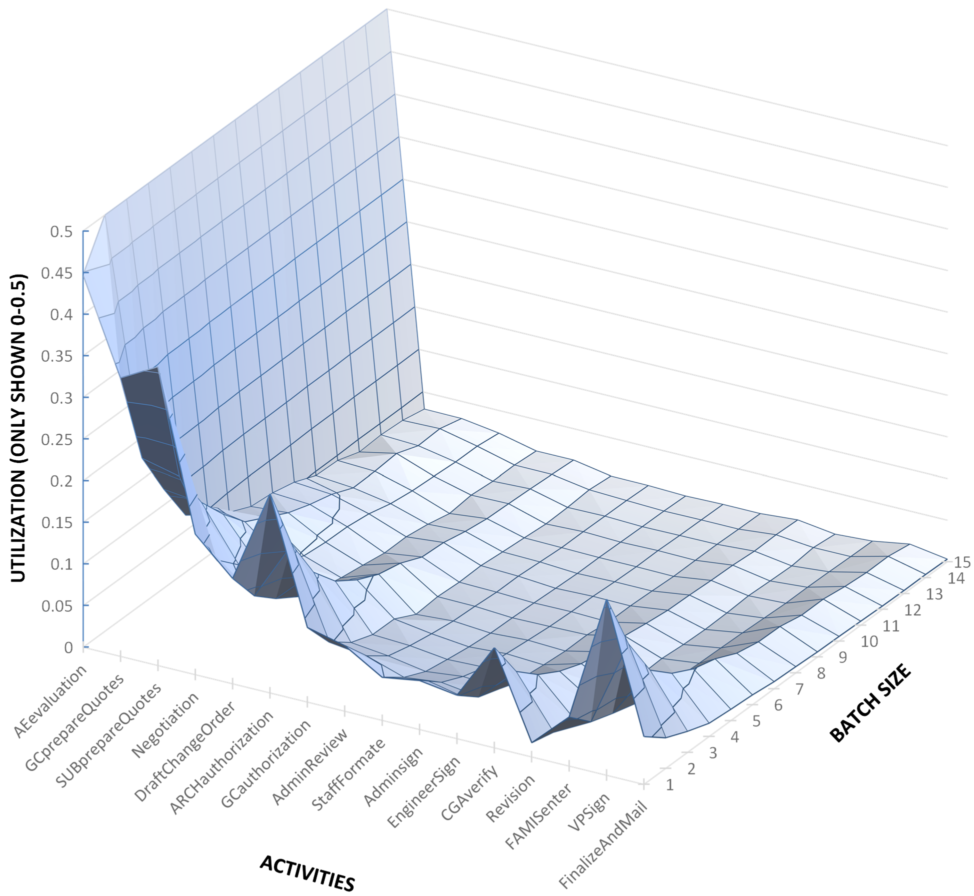


Fig. 7. Utilizations of 16 activities under different batch sizes

this activity (it is analogous to the critical activities in CPM). Therefore, activities with higher utilization level should be expedited to directly reduce the overall duration. Based on the simulation results, several high-utilization activities at the studied university have been identified, which include the architect evaluating the items, subcontractors preparing the quotes, the architect authorizing the change order, the vice president signing the change order, and the CGA verifying the change order. Fig. 7 illustrates the effects of batch size on activities' utilization. As shown, a smaller batch size leads to better overall utilizations for all activities. However, the simulation also finds that in certain cases, better overall utilization does not necessarily mean better overall productivity. Instead, the leveling of utilizations (i.e., make sure all activities have relatively similar utilization level) is more important because it means that work is less congested in particular activities. A better utilization for a single activity refers to a higher utilization. It means that the resources (in this case, the actors) have been fully utilized to perform tasks, or they are busy. However, if at the same time, some activities demonstrate lower utilization level, it means that the workload is not uniformly distributed in the team. In other words,

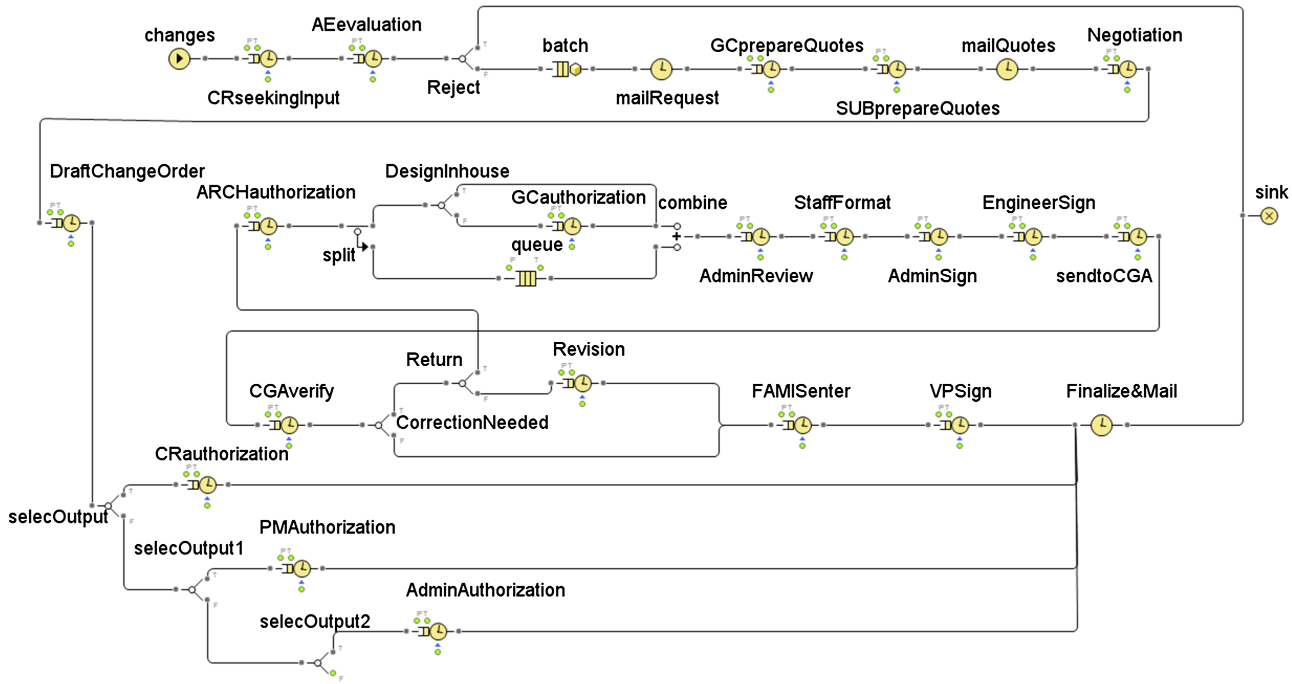


Fig. 8. Alternative change order management process

some actors are waiting for works, whereas some works are waiting for actors. Therefore, for the entire process, a more balanced utilization level across different activities is preferred.

How Should the As-Is Process Be Reengineered?

A closer examination reveals that the change order management process at the university can be reengineered for better efficiency. Specifically, a recommendation has been made to skip the authorization and approval process when allowed. An alternative process was proposed, as illustrated in Fig. 8.

The major modification is adding three thresholds to reduce steps of approval at the university, including *selectOutput*, *selectOuput 1*, and *selectOutput 2*, as shown in Fig. 8. Change orders are categorized and processed based on the dollar amount. For example, when the dollar amount of a change order is less than $5,000, the CR can approve it directly; when the dollar amount is between $5,000 and $10,000, the project manager can approve it; when the dollar amount is between $10,000 and $100,000, the design administrator can approve it; only when the dollar amount is more than $100,000, should the university VP be involved, as specified by the as-is process.

From the case study, the challenge was to determine proper levels of threshold for the involvement of different stakeholders in the approval process. If the thresholds are too low, the majority of the change orders will need complete approval process and thus can help little in reducing the processing time. On the other hand, if the thresholds are too high, it could be more difficult to control risks. The thresholds should be optimized to strike a balance between efficiency and risk, especially the third threshold that determines whether the VP of the university (threshold type 3) will be involved.

According to the archived data, the change item value follows a triangular distribution (0; 500; 10,000). The items, batched into one change order, determine the ultimate dollar amount of the change order. The distribution of change order dollar amount further determines the optimal threshold for whether the VP should be involved (threshold type 3). In other words, the optimal level of threshold is determined by two factors: batch size and dollar amount distribution. Mechanda (2005) has made a recommendation based on the brainstorm session. However, subjective judgement may rule out the real optimal solutions. Therefore, DES simulation has been performed to explore the optimal type-3 threshold under different batch sizes.

Fig. 9 demonstrates the average processing time per change order under different thresholds and batch sizes. Each line represents the most likely processing time per change order with a given batch size and type-3 threshold. For example, when the batch size equals 15, the turn point occurs around $66,000, and thus, $66,000 is the optimal threshold. When the threshold is lower than $66,000, the processing time per change order will be longer. When the threshold is higher than $66,000, the risks will become larger. In this example, $66,000 represents the balanced point.

Fig. 10 shows the simulation results of the productivity under different thresholds and batch sizes. The result supports the findings, as shown in Fig. 9. For example, when the batch size is 15, the turn point is around $66,000.

Weighted productivity refers to the average simulated productivity. In the experiments, because simulation has been repeated for the same set of inputs, the outcomes are distributions instead of deterministic values. To highlight the critical findings, the average values were calculated and plotted, as shown in Fig. 10. Given that the optimal batch size is between 15 and 20, it is suggested that the optimal threshold for VP involvement should be around $66,000.

Evaluating the Improved Process

The proposed improvements, optimizing batch size, accelerating particular activities, and reengineering the process, are expected to expedite the as-is change order management process at the studied university. A comparative experiment was conducted to examine the effects of these improvements. The second improvement, accelerating particular activities, was not included in the comparison because it requires additional resources, and its

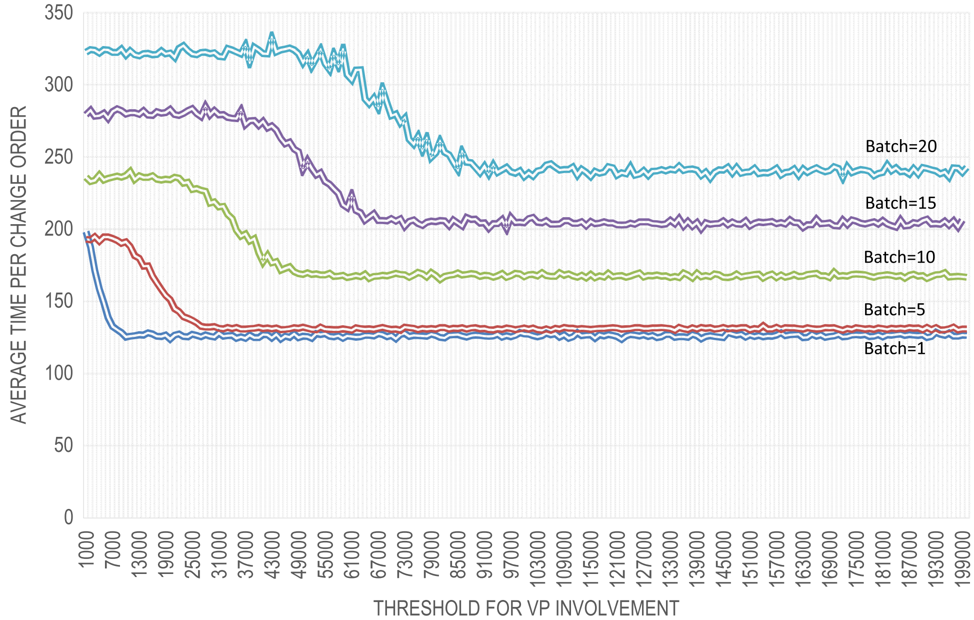


Fig. 9. Average processing time per change order under different type-3 thresholds and batch sizes

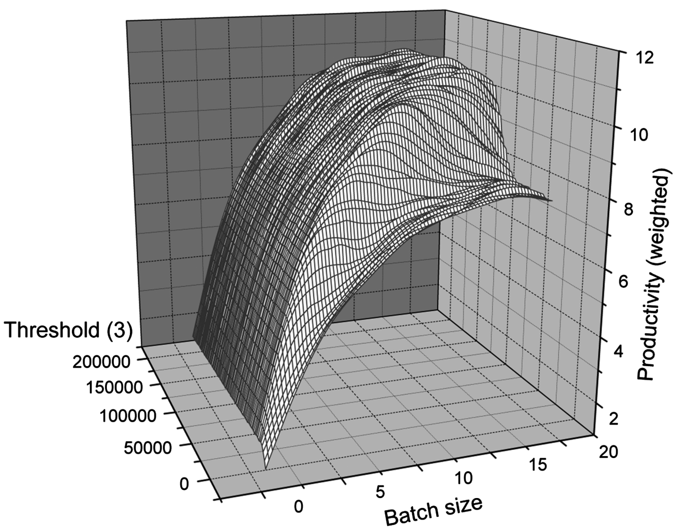


Fig. 10. Overall productivity under different thresholds and batch sizes

impacts in accelerating change order process is obvious. The study is more interested in the improvements without additional resources.

Fig. 11 demonstrates the difference of processing time per change order before and after improvements. As shown, the average processing time per change order has been reduced from 230 to 170 days. A further examination reveals that the average processing time per change item has been reduced from 0.15/day to 0.09/day, and the productivity has been improved from 6.65 items/day to 10.45 items/day.

Although the simulation results indicate the positive effects of the proposed improvements, in terms of reducing processing time of change orders, they should be carefully evaluated before application to real projects. The DES simulation used in this study simplified several situations, such as the actual available time of the actors (e.g., VP), the impacts of change order dollar amount on processing productivity, and the differences across types of projects. Experience gained from previous projects and simulation analysis should be integrated into a reliable recommendation.

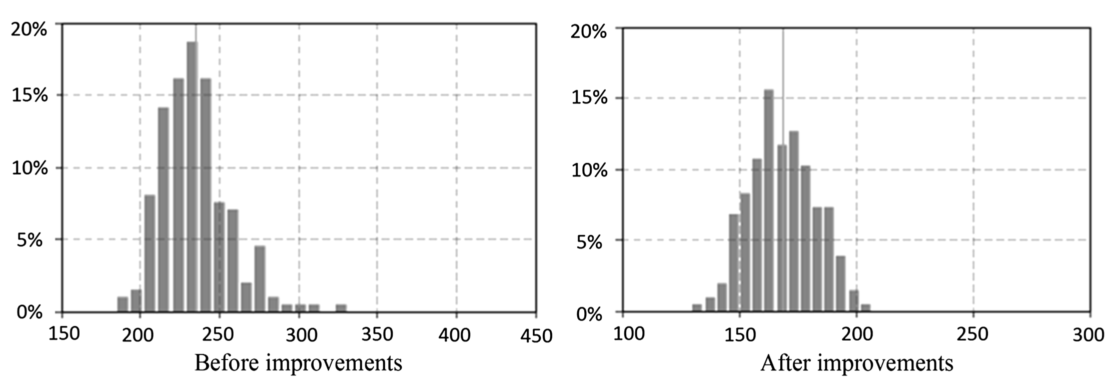


Fig. 11. Processing time per change order before and after improvements

Decision-Making Support and Action Recommendation

The developed model and the case study are not intended to make precise predictions on the productivity and efficiency of change order management. Instead, they aim to support decision making by providing objective evidence. In a what-if scenario exercise, the model was shown to the main stakeholders, including designers, engineers, constructors, and the university administrators, to visualize possible outcomes of an improved change order management process. Findings from the model simulations were deemed to have their policy implications, narrowing down desirable scenarios of the change order management. Having obtained the desirable scenarios, the authors examined their effectiveness in a comprehensive manner, to provide policy recommendations. Ultimately, three recommendations were made.

First, it was agreed that the team should have better control over the batch size of change orders. In previous projects, the university did not require how many change items can be included in a change order. The randomness in batch size has historically added volatility to the process. The number of change items included in change orders ranged from 1 to 39 in finished projects. A recommendation was made that approximately 15 change items should be included in a single change order. The simulation finds that, on average, the overall productivity is expected to increase by 84.9%, reducing the number of change items from 39 to 15, even though the stakeholders originally believed that larger change orders could improve efficiency.

Second, by studying the simulation results, it is possible to find which activities will be the bottleneck of the entire process and where to focus during the change order management. In fact, it was recommended to introduce more architect support in the change order processing. Architects played an important role in the studied case by reviewing, evaluating, and authorizing changes. The simulation findings show that two architect-centered activities are fully utilized, suggesting a need for additional help. In the case study, the high utilization level indicates that the resource (actors) has been utilized to a bigger extent and lacks of room for new tasks. Based on the simulation experiments, it was recommended to hire two more architects to support the change order review and authorizing tasks.

Third, it was recommended to reduce the need of involving the vice president in the change order management. Originally, the vice president must approve and sign every single change order to finalize the entire process, in spite of the size and priority of the change order. Given the busy schedule of the vice president, in practice, this activity has become a bottleneck of the process. The simulation experiments suggest that by setting a threshold of dollar amount for vice president involvement, it is possible to expedite the process significantly. In order to be more concrete, a sensitivity analysis was conducted. Result shows that $66,000 (change order value) is a proper threshold. In other words, if the change order value is lower than $66,000, the vice president approval should be waived. Simulation results indicate that by reengineering the process, the productivity is expected to improve by 43.6%.

In conclusion, although the specific simulation results may vary case to case, depending on the settings, the results demonstrate well how the DES simulation can contribute to enhancing change order management in a real-world setting by providing effective policy guidelines.

Discussion

Previous works, such as Martinez and Ioannou (1999) and Park and Pena-Mora (2003), have tested the usefulness of modeling in tacking construction management problems. Martinez and Ioannou (1999) discussed, in detail, the applicability of different DES paradigm in construction simulation. Their findings show that for most construction problems, AS-based DES is a better fit because most construction management and operations processes can be represented as chain activities. By investigating the constraints and efficiencies of the processes, it is possible to reach a robust decision in most settings (Martinez and Ioannou 1999). A similar paradigm has also been employed by Park and Pena-Mora (2003), who modeled construction changes in a stock/flow manner. This study supplements the previous works because it proves the applicability of modeling, especially DES, in optimizing the change order management process, which is a main argument made by Park and Pena-Mora (2003). It has been found that certain factors affect the efficiency of change order management, which involve the acceleration of individual activities and the reengineering of the entire process. Evaluating and justifying proposed improvements could be a difficult task for project stakeholders. Methods based on subjective judgements have been applied (such as Loch and Terwiesch 1999; Mechanda 2005), but results suggest that these methods may rule out real optimal solutions. For example, based on the brainstorm sessions of the project stakeholders, Mechanda (2005) recommended the optimal number of change items included in a change order to be 10, but the simulation results show that including 15 change items in a change order can further improve the efficiency. Given the interdependencies and nonlinearities of all elements, simulation experiments may provide better decision support.

This study also makes new contributions by showing that PI paradigm is more suited to the change order study, whereas the AS paradigm is recommended more by previous evidence (Martinez and Ioannou 1999). Unlike the AS paradigm, a PI-based DES model is centered on the change orders that flow through the system. In the simulation, it is critical to capture the dynamic states and attributes of change orders. The dynamic changes to change order state and attributes directly affect the successive activities. For example, in a PI-based DES model, passing on a change order to the VP depends on the dynamic attributes of the change order, such as the dollar amount. In contrast, an AS-based DES model is more interested in resource constraints and models the occurrence of certain activities as a pure probability (e.g., at 15%, the chance a change order will need the approval of VP, and at 85%, the chance it will not need the approval of VP). The PI-based models are able to model the change order management process in a more direct way. The second advantage of PI paradigm in change order simulation is the ease of recording change order states. In the case study, the stakeholders were interested in investigating the statistical relationship between the batch size and management productivity. The AS-based DES models have to perform aggregated statistical analysis by assuming the processing time of each step given a certain batch size. It is impossible to differentiate between larger and smaller change orders. For example, when multiple change orders with different batch sizes are modeled, AS-based DES models can only alter the processing time of each step randomly (e.g., Monte Carlo sampling following predefined probability density functions), which completely ignores the numerical correlation between a change order's batch size and its corresponding processing time at each step. In contrast, PI paradigm models change orders as separate objects and document the exact processing time of each step based on the specific attribute values of the change order. The simulation directly documents the correlation between a change order and the outcomes. Therefore, more informative statistical analysis is possible.

In change order management, administrative matters play an important role. Although this study highlights administrative issues as those related to the time required to process the change orders and how they are impacted by batch size, essential activities, and reengineering, administrative matters are mainly outlined and dictated in the contract. Therefore, the potential users of simulation models should only use the findings as additional information for better decision making, instead of any action for revised contractual arrangements. The simulation approach will also be applicable for other construction-related problems, such as safety (Zhao et al. 2015b, a).

Conclusions

Change orders frequently cause disruptions in the planned work schedule and result in increased costs through rework and decreased efficiency to the base contract work in construction projects of all kinds and sizes (Assaf and Al-Hejji 2006; Hanna et al. 1999). Improving the management process of change orders is beneficial to the project in multiple ways, including reducing the cost and risks and encouraging a more trustworthy relationship between stakeholders. This paper tests the applicability of DES in optimizing the change order management process with a case study at a Midwestern land-grant university. Although DES has been applied to tackle a variety of construction problems, the application in change order management is limited. In order to develop a proper DES model for the case study, two prevalent DES paradigms have been compared, including AS and PI. It was found that PI is more suited in the proposed subject. Based on the data of 130 change orders at the studied university and survey results, the as-is change order management process has been mapped. Then, a PI-based object-oriented DES model has been developed, which allows in-depth evaluations on the process. Three potential improvements were proposed (optimizing batch size, accelerating activities, and reengineering process) and evaluated based on the developed model. A SA has also been applied to examine the quantitative impacts of improvement options. The results indicate that PI paradigm outperforms AS in the investigation of change order management process. It is also suggested that the use of DES outperforms subjective judgements on the optimization of change order management.

Appendix I. Objects of Anylogic 7.1 Enterprise Library

AnyLogic is an integrated simulation platform that supports the three major simulation paradigms, including system dynamics, discrete event simulation, and agent based modeling. It builds on object-oriented programming (OOP), and therefore, it is very flexible for various simulation needs and convenient for building hybrid models. As to DES, AnyLogic provides an Enterprise Library that includes necessary objects to create most DES models. Fig. 12 lists the objects used in the DES model presented in this paper.

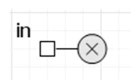
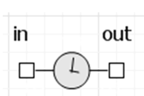
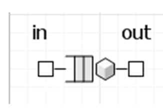
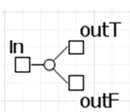
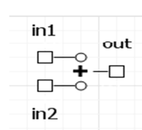
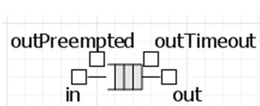
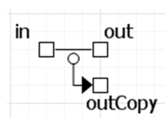
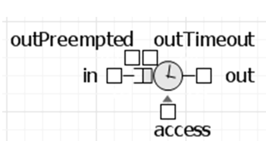
Objects	Description	Objects	Description
	*Source*: the starting point of a process model; it generates entities.		*Sink*: the end point of a process model; it disposes entities.
	*Delay*: it delays entities for a given amount of time.		*Batch*: it converts a number of entities into one entity (batch) by either discarding the original entities or creating a new one.
	*SelectOutput*: it routes the incoming entities to one of the two output ports depending on probabilistic or deterministic condition.		*Combine*: it waits for the two entities to arrive at ports in1 and in2, and produces a new entity and outputs it.
	*Queue*: A buffer of entities waiting to be accepted by the next object(s) in the process flow, or a general-purpose storage for the entities		*Split*: for each incoming entity, it creates one or several copies and outputs them via outCopy port.
	*Service*: it seizes a given number of resource units, delays the entity, and releases the seized units.		

Fig. 12. Library objects used in the model

Appendix II. Sample Code

The first step is to create change items, assign dollar values, and record the timepoints when they entered into the system:

```
Item item=new Item(); // Create a new change item
item.dollarValue= triangular (0,500,10000) // Assign each item a dollar value
item.enteredSystem=time(); // Document the time when the item enters the model
```

Then, one or more item objects will be batched into one change order object according to a predefined parameter (batchSize). The change order's size thus equals batch size, and its dollar value is the summation of all items' dollar values.

```
public void set_batchSize(int newValue) {
batchSize = newValue
}
public int batchSize=10// Customized value of batchSize; for example 10
Order order=new Order();// Create a new order
while (i < batchSize) {// Check if there are enough items to batch to an order
order.size+ = 1;// Add up the order size
order.dollarValue+=item.dollarValue // Add up the dollar value
}
```

Finally, a variety of critical time points can be recorded, including the time point when a change order is batched, drafted, or approved.

```
if (the change order is batched){
order.enteredSystem=time(); //Document the time when the order is batched
}
. . .
if (the change order is drafted){
order.drafted=time(); //Document the time when the order is drafted
}
. . .
if (the change order is approved){
order.approved=time(); //Document the time when the order is approved
}
```

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