Front. Eng. Manag. 2021, 8(1): 109–121
https://doi.org/10.1007/s42524-019-0084-6

RESEARCH ARTICLE

Zhe SUN, Cheng ZHANG, Pingbo TANG

Modeling and simulating the impact of forgetting and communication errors on delays in civil infrastructure shutdowns

Abstract Handoff processes during civil infrastructure operations are transitions between sequential tasks. Typical handoffs constantly involve cognitive and communication activities among operations personnel, as well as traveling activities. Large civil infrastructures, such as nuclear power plants (NPPs), provide critical services to modern cities but require regular or unexpected shutdowns (i.e., outage) for maintenance. Handoffs during such an outage contain interwoven workflows and communication activities that pose challenges to the cognitive and communication skills of handoff participants and constantly result in delays. Traveling time and changing field conditions bring additional challenges to effective coordination among multiple groups of people. Historical NPP records studied in this research indicate that even meticulous planning that takes six months before each outage could hardly guarantee sufficient back-up plans for handling various unexpected events. Consequently, delays frequently occur in NPP outages and bring significant socioeconomic losses. A synthesis of previous studies on the delay analysis of accelerated maintenance schedules revealed the importance and challenges of handoff modeling. However, existing schedule representation methods could hardly represent the interwoven communication, cognitive, traveling, and working processes of multiple participants collaborating on completing scheduled tasks. Moreover, the lack of formal models that capture how cognitive, waiting, traveling, and communication issues affect outage workflows force managers to rely on personal experiences in diagnosing delays and coordinating multiple teams involved in outages. This study aims to establish formal models through agent-based simulation to support the analytical assessment of outage schedules with full consideration of cognitive and communication factors involved in handoffs within the NPP outage workflows. Simulation results indicate that the proposed handoff modeling can help predict the impact of cognitive and communication issues on delays propagating throughout outage schedules. Moreover, various activities are fully considered, including traveling between workspaces and waiting. Such delay prediction capability paves the path toward predictive and resilience outage control of NPPs.

Keywords NPP outage, human error, team cognition, handoff modeling

1 Introduction

Civil infrastructure, such as nuclear power plants (NPPs), are of fundamental importance for the continuous development of urbanization. The proactive operation and maintenance of critical civil infrastructures that deliver services to modern cities are important for maintaining liveable communities while ensuring public safety. NPP outages (known as "shutdowns") are typical examples of operation and maintenance of critical civil infrastructures. In particular, NPPs are among the most challenging

Received May 30, 2019; accepted November 4, 2019

Zhe SUN
School of Sustainable Engineering and the Built Environment, Arizona State University, Tempe, AZ 85281, USA

Pingbo TANG (✉)
Department of Civil and Environmental Engineering, Carnegie Mellon University, Pittsburg, PA 15213, USA
E-mail: ptang@andrew.cmu.edu

Cheng ZHANG
The Zachry Department of Civil Engineering, Texas A&M University, College Station, TX 77843, USA

This research is supported by the US Department of Energy (DOE), Nuclear Engineering University Program (NEUP) under Award No. DE-NE0008403. DOE's support is acknowledged. Any opinions and findings presented are those of the authors and do not necessarily reflect the views of DOE.

accelerated construction projects involving many maintenance and refueling activities, along with a strict schedule and zero-tolerance for accidents (Germain et al., 2014). Such shutdowns are necessary to maintain and identify critical or problematic components or processes of civil infrastructures. Accelerated workflows during civil infrastructure management often involve complex interactions among workers and transitions among multiple tasks, which can cause unexpected and expensive delays (Zhang et al., 2016). Moreover, outage control involves numerous challenges related to human factors and interactions among people working on related tasks (Jang et al., 2013). For example, NPP outages constantly involve hundreds of contract workers for the refueling and maintenance of nuclear reactors (Zhang et al., 2017). Significant amount of training effort is necessary for these contract workers to ensure a good understanding and familiarity of the workspaces and procedures. Moreover, late communications and incorrect information during transfer increases risks of rework or conflictions when sharing certain resources (Germain, 2015).

Transitions (known as “handoff”) between as-planned tasks during a typical outage are even more time-consuming and prone to risks. Such handoff processes typically involve travels between job sites and communications between the management team and workers to exchange information on the work status (Zhang et al., 2017). These activities involve humans, and team cognition is necessary during the handoffs that could accumulate delays within an outage workflow (see Fig. 1). However, the outage manager could hardly track and analyze the time consumption caused by late communication and forgetting during handoffs (i.e., waiting time caused by late communication on available tasks). Thus, delayed communications and forgetting will interrupt workflows and cause rework that results in delays (Sun et al., 2018b). An improved understanding of how delays arise during handoff processes that involve complex interactions between workers and multiple tasks are necessary and crucial to predict delays for the entire workflow.

Several challenges impede the existing scheduling, and process simulation tools fail in diagnosing handoff management issues that cause delays in accelerated civil infrastructure operation and maintenance projects (Wang et al., 2018). Current construction simulation tools simulate only as-planned tasks without considering handoffs during workflows (Zhang et al., 2017). Furthermore, these tools entail difficulty in representing a communication network along with the schedule network (Rozinat et al., 2009). Moreover, the use of traditional simulation tools is even more difficult in representing uncertain cognitive behaviors and analyzing its impact on workflow delays. The majority of the existing scheduling software only simulates a fixed sequence of tasks in a pre-defined schedule, and frequent schedule updating processes that often arise are difficult to represent because of contingencies. The limitations of schedule modeling and simulation tools prevent the mathematical modeling of handoffs in the workflow. Moreover, engineers and researchers are impeded from simulating the potential impact of human errors (e.g., miscommunications) on workflow productivity and in determining optimized scheduling strategies.

NPP outages desire a more robust outage control system for reducing delays. Such a system should automatically identify bottlenecks and respond to human errors or unexpected discoveries during field operations to avoid delays. Given the complexity of the interwoven relationships among the workflow and human communication processes, agent-based simulation modeling is a powerful tool to simulate uncertainties and predict changes in task sequences and productivity variations in an outage workflow (Zhang et al., 2002; Lu, 2003). The current authors developed a simulation model through an agent-based approach to quantitatively examine the impact of cognitive and communication factors on workflow delays during NPP outages. The developed simulation platform consists of 1) a workflow model based on a past NPP outage schedule and 2) a developed handoff model according to the handoff process observed from the field. In particular, the workflow model represents the spatial-temporal relationship between tasks within an outage workflow. Such a relationship specified the precedence relationship between tasks, locations, and random task durations that follow uniform distributions. The developed handoff model represents human activities (e.g., travel, communication) that fills in the gap between the connected tasks. The current study aims to use the developed handoff model to estimate the impact of human and team cognition on

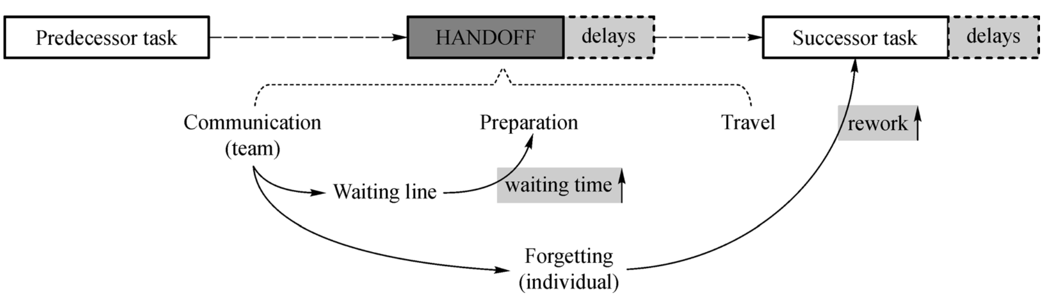

Fig. 1 Framework for assessing the impact of cognitive and communication factor on workflow delays.

workflow delays.

The remainder of this paper is organized as follows. Section 2 provides a detailed literature review on 1) the practical human and team cognition issues in the current practice of NPP outage control, and 2) simulation-based modeling techniques to assess the impact of human factors on workflow productivity. In particular, Section 2.1 reviews the studied human factors at the individual/team level involved in construction workflows and the corresponding impact on workflow productivity. This section also introduces the focus of this study to understand the impact of forgetting (individual level) and late communication (team level) on workflow productivity. Section 2.2 lists the limitations of using current scheduling practices and simulation tools to assess and predict the impact of human factors on workflow productivity and safety. Section 3 describes the developed handoff model (Section 3.1) to assess the impact of forgetting (Section 3.2) and late communication (Section 3.3) on the delays of maintenance workflows during NPP outages. Section 4 shows the simulation results of the impact of forgetting (Section 4.1) and late communication (Section 4.2) on workflow delays, as well as the practical values of the developed handoff model and use-case scenarios (Section 4.3).

2 Literature review

2.1 Human and team cognition NPP outage control

Managing NPP outages is difficult owing to the coordination and collaboration of numerous maintenance and refueling activities within a short period (Hadavi, 2008). Human and team cognition have played a critical role in affecting the productivity and safety of civil infrastructure operations and maintenance activities (Promsorn et al., 2015). Table 1 lists some of the studied human factors in the literature that proved the huge impact of human and team cognition on civil infrastructure operations and maintenance activities. Previous studies have determined that an individual's forgetting, fatigue, and experience levels can seriously affect workflow productivity and safety (Sun et al., 2018a). Moreover, team behaviors (e.g., communication, situation awareness, culture) also contribute to numerous operation failures. The current study focuses on understanding the impact of forgetting and communication on delays during maintenance workflow.

Tedious refueling and maintenance tasks during NPP outages require workers to perform the scheduled tasks at the right time and place. Workers are required to follow the exact procedure and complete the required tasks on time to avoid severe delays. However, workers can still forget certain steps specified in the procedure while performing the scheduled tasks (Pyy, 2001). Forgetting errors (known as "omission errors") is the most frequent human error in valve maintenance tasks, causing 14% of valve maintenance failures (Neboyan and Lederman, 1987; Love and Li, 2000; Pyy, 2001; Kim and Park, 2012). Such errors are constantly associated with additional costs because of reworks (Love and Li, 2000).

Communication between the worker and management teams during handoffs is critical for successful information exchanges, while the existing schedule software tools could hardly integrate communication modeling into the schedule simulation to examine the impact of communication errors on workflow efficiency (McKendall et al., 2008; Hu and Mohamed, 2010). The three forms of communication in outage control practice are as follows: 1) radio communication among people within the containment, 2) telephone communication among people outside the containment, and 3) face-to-face communication (Gorman et al., 2012). Face-to-face communication is the last form people would like to use if other forms of communication failed because workers may have to leave the work areas and lose significant amount of working time (Abdel-Monem and Hegazy, 2013). In particular, communication is one of the most significant aspects of team cognition and represents the interactions among team members (Cooke, 2015). Such interactions eventually turn a set of individual knowledge into team knowledge and increase team situation awareness for an improved team decision-making (Cooke et al., 2005). In addition, communication flow and

Table 1 Human factors at the individual/team level during construction workflows

Level of human factors	Definition	Examples	References
Individual level	Individual cognition reflects the mental action or process of acquiring knowledge and understanding, which includes such aspects as attention, memory, judgment, and evaluation (Von Eckardt, 1995; 2001)	Forgetting	Love and Li (2000); Nembhard (2000); Nembhard and Bentefouet (2012)
		Fatigue	Lee and Pena-Mora (2005); Seo et al. (2016); Techera et al. (2018)
		Experience level	Lloyd (2003); Sambasivan and Soon (2007); Sacks et al. (2013); Scott et al. (2015)
Team level	Team cognition reflects the team capabilities when teams are performing cognitive activities as a unit (Cooke, 2015; Cooke et al., 2008)	Communication	Sambasivan and Soon (2007); Abdel-Monem and Hegazy (2013); Liao et al. (2014)
		Team situation awareness	Gorman et al. (2006); Demir et al. (2017)
		Culture and leadership	Fang et al. (2006); Liao et al. (2014); Zhang et al. (2019)

content have long been cited as the indexes for measuring the effectiveness of communications in the cognitive processes (Cooke et al., 2005). Shared knowledge among team members is necessary for a complex network (Cooke et al., 2005). The variances of task durations and handoffs introduce numerous uncertainties during the outage, which significantly increases the risks of delays (Wakker et al., 2003; McKendall et al., 2008). Moreover, another concern may be the significant portion of contract personnel involved during outages with limited knowledge and experiences in outage activities and environments. The lack of familiarity with outage decision contexts could also cause risks of miscommunication and errors in teamwork (Cooke et al., 2013). The timing for communication likewise substantially affects team performance in terms of productivity (Smart and Shadbolt, 2012). However, limited research has quantified the impact of early/late communication during a complex workflow.

2.2 Simulation to assess the impact of human factors on workflow productivity

Project schedules often specify the spatiotemporal relationships between the connected tasks and resources (e.g., workers, equipment) required to complete such tasks (Alzraiee et al., 2015). Project managers constantly rely on the schedule to plan, execute, and manage projects (Alzraiee et al., 2013). However, traditional schedule models often failed because of the lack of precise representations of interwoven relationships among workers, schedule, and workspace (Hu and Mohamed, 2010). Computer-based simulation is a scientific tool to develop models on the bases of real schedules and examine system behaviors under uncertainties (AbouRizk, 2010). The use of computer simulation tools to model and simulate complex interwoven relationships within operational processes could help in substantially revealing how the system behaves under different conditions (Abourizk et al., 2016).

Furthermore, integrating handoff processes into existing construction simulation tools is challenging. The tedious communication activities between project personnel and resource-sharing processes in handoffs require detailed representations to support accurate handoff modeling (Heo and Park, 2010; Promsorn et al., 2015). Traditional scheduling tools, such as Gantt charts or Program Evaluation Review Technique (PERT), have been widely used in the current practice of project control (Jan et al., 2013). However, these workflow representations could hardly represent how human behaviors influence task executions and the complex interaction between different tasks and resources. Under the influence of handoffs, the task sequence in NPP outages is changing frequently, while widely used scheduling tools could not effectively analyze task sequence updates and how uncertain human behaviors and field events influence task execution sequences. Thus, new simulation models are necessary to integrate the representations of human behaviors (e.g., communications, mistakes in reporting and executing tasks) and unexpected events into the schedule analysis methods.

To model the detailed spatiotemporal interactions among tasks during outages, the uncertainties of the duration of tasks, travels, and communication should be considered while modeling the detailed interactions. Unfortunately, current construction simulation software cannot model the uncertainties during handoffs caused by the changes in task sequences in job–shop schedules. In job–shop problems during NPP outages, workers often use a set of machines to work on tasks with specified procedures (Chaudhry and Khan, 2016; Kundakcı and Kulak, 2016). Unknown task sequences in a job–shop workflow will lead to uncertainties on the traveling time and task preparation time because these processes are related to the successor and predecessor tasks.

3 Handoff modeling for assessing the impact of human factors (forgetting/late communication) on the delays of maintenance workflows during NPP outages

In general, the proposed simulation-based model input the as-planned schedule and uncertainties found from the interview and documented historical records, and calculate the delays caused by the identified uncertainties. The proposed model represents and simulates the detailed spatiotemporal interaction between tasks (e.g., processor and successor task relationships) and human resources (e.g., management team and work teams). These relationships are constraints that determine how the detailed spatiotemporal interaction between tasks and human occur within the workflow model. Moreover, the model represents information flows across multiple teams in a centralized communication network.

The proposed simulation-based modeling method (see Fig. 2) integrates a workflow model based on the NPP outage schedule and a developed handoff model according to the handoff process observed from the field. The workflow model aims to represent the detailed interactions among tasks in an accelerated construction workflow. However, the handoff model simulates detailed human activities during handoff processes (i.e., communication, travel, and wait). The developed handoff model represents detailed interactions among individuals within and across groups (communications between the supervisor and work team).

3.1 Human activity modeling

Work teams and the supervisor need to communicate to exchange the as-is workflow information. The supervisor first needs to collect field information by communicating with all work teams and assign available tasks to certain teams. The work team will only receive calls from the supervisor when a task is available. The authors introduced the "worker" and "supervisor" agents in human activity modeling to model the workers and supervisor's behaviors. In particular, the authors modeled the communication behaviors for exchanging task information between two agents. Such information contains two parts: 1) the amount of all tasks in the workflow for a work team, technical details of the tasks, and general timing and resource needs; and 2) notifications on the completion of predecessors of the tasks assigned to a work team. However, the authors assume that the trained work teams are familiar with the first part of the task information. The communication modeled in the current study only represents 1) notifications from workers to supervisor on the completion of predecessor tasks and 2) notifications from supervisor to workers on available tasks. For the worker agent, each work team has four functions, namely, working, communicating, traveling, and waiting (see Fig. 3). Thereafter, the workers may enter into the working status to execute the scheduled task once they receive the notifications from the supervisor. When in working status, the timer of the current task starts counting down. After the timer of the current task becomes zero, the worker should switch to communicating status. The communicating status specifies the worker needs to report to the supervisor on the completeness of the current task so that the supervisor can mark complete on the task. When the worker enters the communicating status, the communication timer of this worker starts to countdown until the communication with the supervisor is over. Thereafter, the status of the work team becomes waiting if no incoming calls from the supervisor. The worker will remain waiting status until he/she receives a phone call from the supervisor on the available work packages. The work can start to travel to different job sites or workstations at the same job site.

In this NPP outage scenario, the supervisor agent should 1) answer the phone calls from the work team and record the information on the completed tasks and 2) inform the work team that specific tasks are ready to be worked on after the supervisor receives a phone call reporting a finished task (see Fig. 4). The supervisor will continue

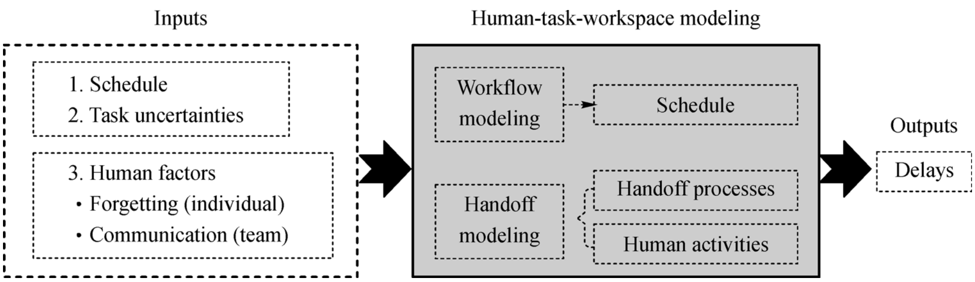

Fig. 2 Overall methodology.

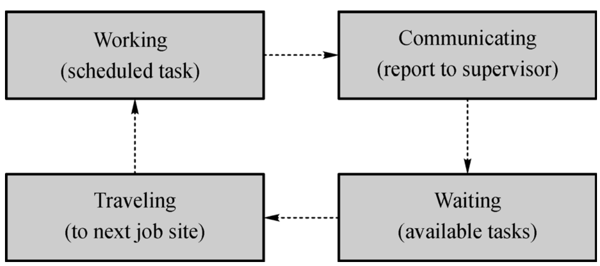

Fig. 3 Status transition of the worker agent.

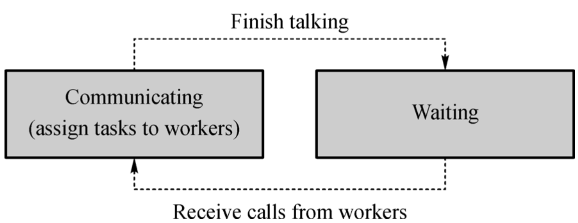

Fig. 4 Status transition of the supervisor agent.

monitoring the progress of the workflow by acquiring field information from workers and check which task is available. Thereafter, the supervisor will make a phone call to inform the worker agent who is responsible for the available task. If no tasks are available, then the supervisor will remain in the waiting status. At the beginning of the workflow, the supervisor is responsible for initiating the workflow by informing the workers that the first task is available, thereby enabling the workers to start working on the first task.

3.2 Scenario 1: Assessing the influence of forgetting on pump maintenance workflows

This section presents a simulation model that uses the workflow of pump maintenance activities around cooling towers with the developed handoff model to assess the impact of forgetting on workflow delays. Pump maintenance is critical during NPP operation, and problematic water pumps will cause a reactor meltdown accident. The studied activities for pump maintenance workflow include visual inspection, pump maintenance, and functional surveillance testing. To understand how forgetting errors affect pump maintenance workflow, the authors have integrated the Ebbinghaus Forgetting Curves as a function into the human activity model to model the forgetting behaviors of workers. Figure 5 visualizes the overall workflow for this scenario. In this scenario, workers have to communicate with their supervisor and complete pump maintenance activities at nine job sites.

The simulation model to assess forgetting errors on pump maintenance workflow defines two types of relationships in the model, namely, the spatial relationships among tasks at different job sites, and the precedence relationships among tasks. Spatial relationships specify the locations of the job sites and require work teams to travel between job sites to complete all the required tasks. In the pump maintenance workflow, three work teams should collaborate and complete the pump maintenance works at nine job sites. Precedence relationship specifies the task sequence at every job site. For each pump, the inspection team should first conduct a visual inspection of the valve conditions and decide the required maintenance activities. Thereafter, the mechanical team should conduct the maintenance work on that pump based on the inspection team's judgment. Lastly, the surveillance testing team should finalize the pump maintenance to ensure that the pump is functional (see Fig. 6 and Table 2). During the pump maintenance workflow, all work teams are required to communicate with the supervisor to 1) report the completion of the current work when they finish; and 2) obtain information on task availabilities. The supervisor is required to continue monitoring the field operations by communicating with all work teams.

In the developed simulation model, the durations of all tasks are modeled by following uniform distributions. For example, the duration of Task 1 in Table 2 was modeled as 20–40 minutes, which means that the probability of task duration falling between 20 and 40 min is equal. Moreover, the simulation model will randomly select a number

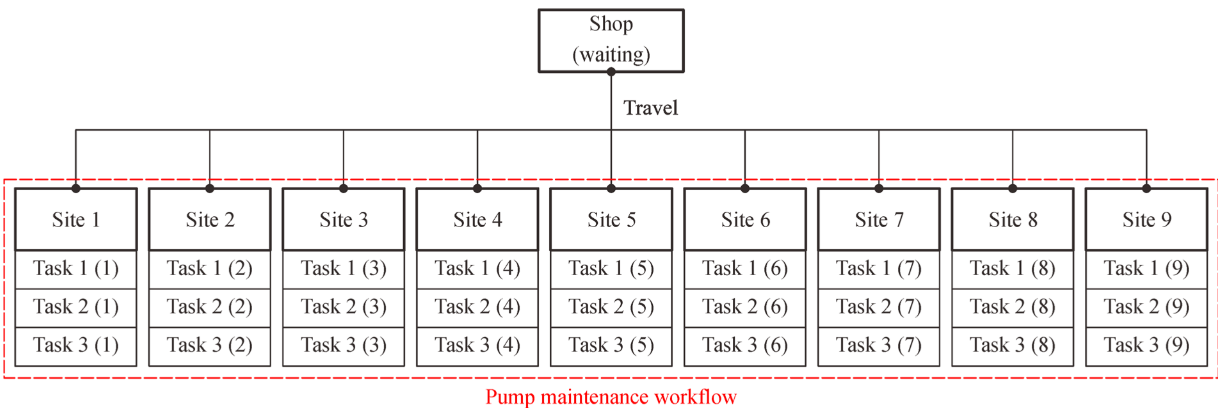

Fig. 5 Overall workflow for Scenario 1.

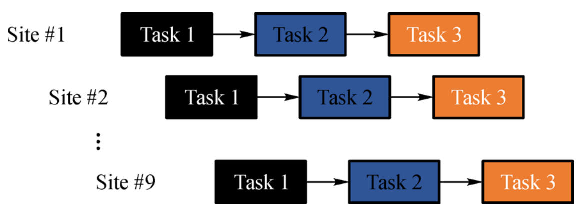

Fig. 6 Pump maintenance workflow in cooling systems.

Table 2 Detailed task information in the pump maintenance workflow

Task ID	As-planned task	Locations	Resources	As-planned durations (min)
Task 1	Visual inspection	Site #1 to #9	Inspector	20–40
Task 2	Maintenance	Site #1 to #9	Mechanic	30–60
Task 3	Functional surveillance testing	Site #1 to #9	Tester	30–60

between 20 and 40 as task duration in each run of the simulation model. Overall, the authors run the simulation model 10000 times to assure the validity of the model.

The current practice of NPP outage management requires a huge amount of additional contract personnel to complete all scheduled tasks within a strict time window. However, the recruited workers with different education backgrounds, prior work experiences, and cognitive capability may have different interpretations of their assigned work packages. Professionals with extensive work experience in NPP outages will be more familiar with the required procedures, whereas contract workers with limited experience on outage workflows require more practice to complete the assigned tasks correctly. Thereafter, forgetting issues on these contract workers will lead to rework, delays, and budget overrun. The developed forgetting model in the simulation is based on the Ebbinghaus Forgetting Curves, which describes how the possibility (P) of forgetting to complete certain parts of the work decrease with time (t). The Ebbinghaus Forgetting Curves contains two parameters: Pre-knowledge level (α) and memory decay speed (β).

The current research studied how the memory decay speed (β) of different workers cause forgetting errors and lead to workflow failure and delays. Such forgetting varies based on when the work team begin their next available task because they receive task availability information from the supervisor. The work team may forget certain steps in the specified procedure if the task information had been received a long time ago. Such forgetting errors will cause the failure of completing the task. Table 3 lists the studied forgetting curves from previous studies. These studies have shown different forgetting behaviors among different types of people (e.g., students, new graduates with limited work experience, experienced workers) and generated different curves.

Table 3 Forgetting curves from previous studies ($\alpha = 1.0$)

Forgetting curve	Memory decay speed (β)	References
$P = \alpha e^{-\beta t}$	0.01	Loftus (1985)
	0.05	Loftus (1985)
	0.1	Anderson and Tweney (1997)
	0.2	Anderson and Tweney (1997)
	0.5	Anderson and Tweney (1997)
	1.0	Anderson and Tweney (1997)

3.3 Scenario 2: Assessing the influence of late communication on valve maintenance workflows

This section presents a simulation model that uses the workflow of valve maintenance activities for the main turbine system with the developed handoff model for assessing the impact of late communications on workflow delays. Valve maintenance is a critical activity that needs work teams to enter the containment for conducting maintenance activities. Moreover, work teams need additional handoff activities (i.e., technical briefing, dosimetry checking, tool pick-up/return, and check available work package) in the radiation protection island before and after the scheduled tasks. However, the radiation protection island is a compact place where different workstations should be shared among all work teams (i.e., work teams cannot pick-up tools if another work team has already occupied the tool pick-up station). Thus, communication between supervisor and work teams are important to deliver the message and avoid additional waiting times during handoff. The authors have introduced a substantially comprehensive handoff process model to considerably understand how the late communication affect the handoff processes and eventually lead to workflow delays. Figure 7 visualizes the overall workflow for this scenario. In this scenario, workers have to go through the indoor workspace and complete the handoff processes to get prepared for the valve maintenance activities at Sites A and B.

The tasks simulated in the experiment are valve maintenance at Sites A and B and handoff at an indoor workspace. Figure 8 visualizes the entire as-designed workflow at Sites A and B. Blocks with the same color are the tasks using the same labor team (i.e., insulator—black; electrician—blue; mechanic—orange). Tasks sharing the same team cannot be executed simultaneously. The detailed task information is presented in Fig. 8 and Table 4.

The indoor workspace (see Fig. 9) simulates the handoff processes within the radiation protection island and prepare work teams for working within the containment. Such handoff processes include checking available work packages, dosimetry checking, getting technical debrief, and picking up tools (e.g., earplugs). All work teams should go through a specific handoff process (different work teams will have a different sequence of station visiting) in an indoor workspace to be ready to work inside the containment for valve maintenance. Table 5 illustrates

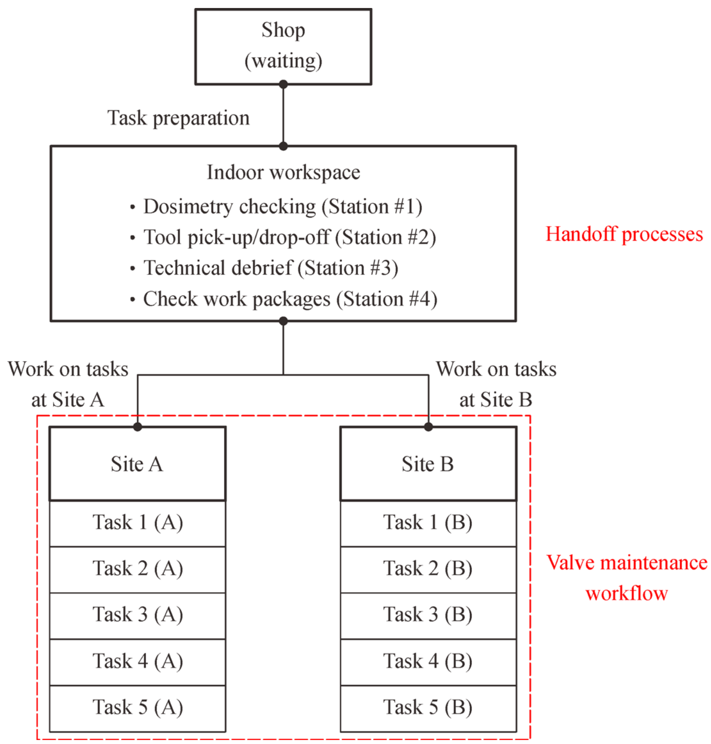

Fig. 7 Overall workflow for Scenario 2.

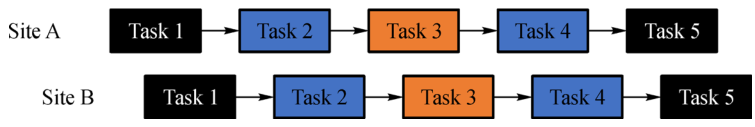

Fig. 8 Valve maintenance workflow.

Table 4 Detailed task information in a typical valve maintenance workflow

Task ID	Task name	Location	Resource	Avg. task duration (min)
Task 1	Remove the insulation from the valve	Site A/B	Insulators	30
Task 2	De-term the motor operator	Site A/B	Electricians	45
Task 3	Maintain the valve	Site A/B	Mechanics	60
Task 4	Re-term the motor operator	Site A/B	Electricians	45
Task 5	Re-install the insulation	Site A/B	Insulators	30

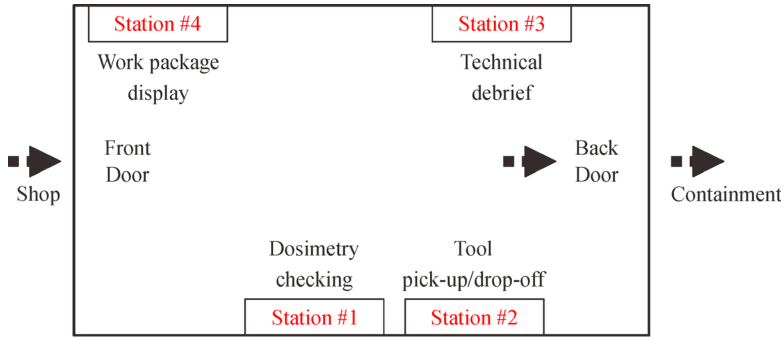

Fig. 9 Indoor workspace setup for handoff processes.

Table 5 Handoff processes in the indoor work environment

Worker	Enter/Exist containment	Sequences of station visiting
Insulator	Enter	4 → 1 → 2 → 3
	Exit	1 → 2 → 4
Electrician	Enter	4 → 2 → 1 → 3
	Exit	1 → 4
Mechanic	Enter	4 → 2 → 3
	Exit	1 → 2

all sequences of station visiting for work teams while entering or exiting the indoor workspace.

Once a work team completes a task and travel back from the containment, all team members should go through certain processes in the radiation protection island for dosimetry checking, drop off tools, and check other available work packages. According to the practice of handoff processes among tasks, the authors found out from the interview that workers may have different objectives before/after they start working on scheduled tasks. Thus, different work teams may have different moving patterns in the indoor workspace during handoff. For example, the insulator typically goes to Station 4 first to check the work packages; next goes to Station 1 for dosimetry checking and picks up their tools at Station 2; then goes to Station 3 for technical debrief before they enter into the containment. However, the mechanic does not need to go to Station 1 for dosimetry checking before entering the containment. The time that each work team spends at different stations may also be different from one another. Table 6 presents a detailed handoff activity information for different work teams.

Communication during the handoff process can also be a huge concern because some work teams may forget to report to the supervisor on the completion of current tasks, thereby causing delays. The authors' field observations indicated three major types of uncertainties involved during the handoffs and cause late communications between the supervisor and workers. For example, workers may miss the voice message from the supervisor and do not realize an available work package for them to work on. Moreover, workers could report the work status late to their supervisors after finishing their work. The supervisor could send out the available task information late to the workers of the successor tasks when the supervisor is simultaneously coordinating several tasks with different workers. In this scenario, the authors have simulated the late report and attempted to understand the impact on workflow delays. The authors model the late report by modifying the communication function of the worker agent. Accordingly, workers are allowed to report the completion of their tasks after a certain time once they complete certain tasks. This modification will set up a specified timer and ask workers to report to the supervisor for the task completion when the countdown of the timer reaches zero. In this case, the workers will be able to report to the supervisor when they are either traveling, waiting, or in the handoff processes in the indoor workspace.

4 Results and discussion

4.1 Impact of forgetting on workflow delays

As shown in Table 7, the authors have examined the impacts of studied forgetting curves on delays of pump maintenance workflow. In the simulation, the authors defined the two indices to illustrate such impacts. The first index is the likelihood of workflow failure, which is a case when a worker has forgotten certain steps of the tasks, thereby causing rework. To calculate the probability of rework, the authors have simulated the workflow execution processes with human forgetting probability parameters integrated into the simulation model for 10000 times. A certain number of the 10000 executions of the workflows will fail to proceed and complete due to the randomly generated forgetting events that stop the continuation of the working processes and result in reworks. The authors counted the numbers of simulation results (out of 10000 simulations) where rework occurred owing to forgetting. The second index is the delays in the workflow caused by forgetting and reworks. The authors first executed the simulation model for 10000 times with a deactivated forgetting model and set the average overall workflow durations as the baseline. Thereafter, the authors activated the forgetting model in the simulation and executed the simulation model for another 10000 times to assess the impact of forgetting and rework on workflow duration. The authors calculated the delays by comparing the differences

Table 6 Tasks during handoff for valve maintenance

Task name	Station	Resource	Avg. task duration: Enter (min)	Avg. task duration: Exit (min)
Dosimetry checking	Station 1	Insulator/Electrician/Mechanic	5/5/NA	5/5/5
Pick-up/Drop-off tools	Station 2	Insulator/Electrician/Mechanic	5/10/15	3/NA/5
Technical debrief	Station 3	Insulator/Electrician/Mechanic	5/10/15	NA
Check work packages	Station 4	Insulator/Electrician/Mechanic	5/5/5	3/3/NA

Note: NA: not applicable.

Table 7 Impact of forgetting errors on the delays of pump maintenance workflow

Forgetting curve	Memory decay speed (β)	Probability of workflow failure	Delays (%)
$P = \alpha e^{-\beta t}$ ($\alpha = 1.0$)	0.01	0.14	6.72
	0.05	0.51	12.77
	0.1	0.71	17.14
	0.2	0.80	26.22
	0.5	0.96	54.12
	1.0	0.98	68.24

between workflow durations with the forgetting model activated and the baseline duration.

The authors first execute the simulation model by deactivating the forgetting function of worker agents. The results show that the baseline workflow duration is 595 minutes. Thereafter, the authors examined how forgetting errors could induce risks of workflow failure and delays using the studied forgetting curves. The simulation results indicate that the memory decay speed could have a great impact on both workflow failure and delays. The probability of workflow failure and delays will increase with increased memory decay speed.

The results indicate that the forgetting errors of workers could induce risks of rework and lead to delays to NPP outage workflows. Such forgetting errors are often associated with poor pre-knowledge on the scheduled tasks owing to insufficient training, limited experience when conducting certain as-planned tasks, and cognitive capability of individuals. The results also show that the probability of workflow failure (probability of reworks occurred in workflow) had increased when the cognitive capability of an individual decreased (increase forgetting speed). That is, reworks will likely occur and cause delays for individuals who have limited recall capability to remember work details.

4.2 Impact of late communication during handoffs on workflow delays

Late communications could accumulate and cause severe delays to the handoff processes. For example, given that handoff processes involve traveling, communications, and task preparation activities (e.g., tool pick-up/return, technical briefing, security checking), late communication would cause conflicts between workers in resource sharing (e.g., different workers may simultaneously come to a station for tool pick-up) and result in delays. Moreover, a scheduled task on the critical path has zero-tolerance of delays during the handoff process. To better understand how late communication affect the workflow delays, the authors 1) conducted 20 trials of laboratory experiments using the developed workflow and handoff model to capture workers' late-report behaviors (i.e., worker reports the completion of each task late to the supervisor); and 2) conducted computational simulations to simulate how such late-report behaviors affect overall workflow delays. The authors hired participants from the construction management program of Arizona State University and provided detailed training on the experiment. During the experiment, the authors assumed the role of an observer and attempted to capture the late-report behaviors by the participants (documented in Table 8).

Table 8 Late-report captured during the laboratory experiments

Task	Worker	Late report (Delayed time: min)	Trial
Task 1 (A)	Insulator	2.6	2
Task 3 (A)	Mechanic	1.5	2
Task 4 (A)	Electrician	1.8	7
Task 1 (A)	Insulator	0.5	12
Task 3 (B)	Mechanic	3.0	14
Task 4 (A)	Electrician	1.2	18
Task 1 (B)	Insulator	0.8	18

According to the field observations, the captured average delays caused by late-report can be up to 30 min (durations in the laboratory experiment are scaled back ten times). Thereafter, the authors simulate a 30-min late-report during the handoff process in the simulation model. For example, a 30-min late-report behavior is simulated after the insulator finished Task 1 (A) due to the insulator forgetting to report to the supervisor that Task 1 (A) has been completed. That 30-min late-report behavior eventually leads to a nearly 30-min delay to the overall schedule because Task 1 (A) was a critical-path task.

Table 9 shows that Task 4 (B) is more vulnerable because the workflow is more sensitive to the delays of handoff (30 min, 5.28%). Delays on Task 5 at Sites A and B had the least impact on the overall workflow duration. Given that a 30-min late-report has been added to one of the tasks in the workflow, the extension on the task duration will affect the actual task and the handoff process of other tasks. In particular, the supervisor will receive the field information late owing to the late-report and cause delays to the successor task. Such late-report behaviors may also cause extended occupation on a certain station during the handoff processes by having a phone call. The extended occupation on the shared stations will eventually cause additional waiting time for other workers who are waiting to use the station. If specific tasks are delayed, then the probability of having conflicts among different work teams while in the handoff process would increase. The waiting time during handoff will also increase owing to the conflict, thereby causing additional delays to the workflow.

Table 9 The sensitivity of the 30-min late-report of each task

Site	Task	Worker	As-planed task duration (min)	Late report (min)	Workflow duration (min)	Workflow delays (min)	Probability
A	Task 1	Insulator	30	60	597	29	5.10%
	Task 2	Electrician	45	75	584	16	2.82%
	Task 3	Mechanic	60	90	577	9	1.58%
	Task 4	Electrician	45	75	585	17	2.99%
	Task 5	Insulator	30	60	568	0	0%
B	Task 1	Insulator	30	60	577	9	1.58%
	Task 2	Electrician	45	75	570	2	0.35%
	Task 3	Mechanic	60	90	586	18	3.17%
	Task 4	Electrician	45	75	598	30	5.28%
	Task 5	Insulator	30	60	568	0	0%

For example, additional waiting time may occur while Task 4 (B) is delayed. The reason is that the tool returning process of the electrician team may be in conflict with the tool pick-up process of the insulator team that is about to start on Task 5 (B).

4.3 Discussion on the practical values of the developed handoff model and use-case scenarios

The proposed handoff modeling resolved the primary concerns in detailed workflow modeling to understand the impact of human factors on workflow productivity. In particular, the developed simulation platform has integrated communication and traveling activities into an interwoven workflow for revealing the impact of forgetting and late communication on workflow delays. Such a simulation platform represents the detailed interactions among human, workspace, and tasks, and serves as a powerful tool to simulate human and task-related uncertainties. By using the developed simulation platform, users will be able to predict changes in task sequences and productivity variations in a workflow. The authors envision that the extensions of the developed simulation platform could 1) benefit the project manager to better assess potential delays and economic losses; 2) assist the project scheduler in updating the schedule accordingly based on the simulation results (i.e., find optimal slot to insert new tasks); 3) help examine optimal communication protocols to ensure efficient communication between project participants (i.e., supervisors and workers); and 4) help develop better training programs that prepare workers with sufficient knowledge for scheduled tasks.

The developed simulation platform could also be useful for outage control and other types of project schedule analysis where communications during handoffs between tasks cause main delays. For example, the developed handoff modeling platform could help simulate the communication between air traffic controllers and pilots during air traffic controls to assess and predict the delays and accidents (e.g., runway incursion, loss of separation) in air traffic operations. Moreover, bridge inspection requires the cognitive capabilities of an engineer to recognize structure defects and describe in detail to ensure that the management team has a proper understanding of the bridge condition. Misunderstandings or misinterpretations of the inspection results could lead to the improper design of maintenance strategies during bridge maintenance. The developed platform could also serve to help estimate the potential failures of field inspection operations.

5 Conclusions

Precisely estimating workflow duration is extremely important to maintain productivity and safety in an NPP outage project. However, the uncertainties of the tasks and human behaviors bring significant difficulties to precise estimation. The precise estimation of the task duration of each task is relatively tricky. However, spending additional resources to determine the "real-time truth" on risky tasks is possible. Thus, identifying the list of vulnerable tasks in workflow during the planning phase can guide the management team to allocate resources better, thereby achieving resilient NPP outage control. The authors proposed an agent-based simulation according to an as-planned workflow. According to the simulation results, task deviations and delays during handoffs of certain tasks play a significant role in affecting the overall duration of the workflow. This simulation model can help identify the vulnerability of a given schedule by estimating the sensitivity of delays due to each task. The simulation result also shows that the proposed handoff modeling can provide a reliable reference to improve the monitoring strategies in NPP outage workflows.

The research findings indicate that the detailed interactions among tasks, individuals, and resources are significant concerns that cause delays during outages. Hence, reducing the time wasted and error rates caused by uncertainties (e.g., communication error, time for communication) in the schedule maintenance workflows and handoff processes are critical to ensure the on-time completion of outages. Overall, the authors plan to use the developed simulation platform to 1) examine whether additional communication can help increase workers' familiarity with tasks, and 2) examine whether the early-call during handoff process could reduce delays (supervisor will call work team 15 min ahead of time, according to the as-planned schedule, to inform the work team that his/her successor task is about to finish).

References

Abdel-Monem M, Hegazy T (2013). Enhancing construction as-built documentation using interactive voice response. Journal of Construction Engineering and Management, 139(7): 895–898

AbouRizk S (2010). Role of simulation in construction engineering and management. Journal of Construction Engineering and Management, 136(10): 1140–1153

Abourizk S M, Hague S A, Ekyalimpa R (2016). Construction Simulation: An Introduction Using Simphony. Edmonton, Canada: University of Alberta

Alzraiee H, Zayed T, Moselhi O (2013). Assessment of construction operations productivity rate as computed by simulation models. In: Proceedings of the 2013 Winter Simulation Conference: Simulation—Making Decisions in A Complex World. IEEE Press, 3225–3236

Alzraiee H, Zayed T, Moselhi O (2015). Dynamic planning of construction activities using hybrid simulation. Automation in Construction, 49: 176–192

Anderson R B, Tweney R D (1997). Artifactual power curves in forgetting. Memory & Cognition, 25(5): 724–730

Chaudhry I A, Khan A A (2016). A research survey: Review of flexible job shop scheduling techniques. International Transactions in Operational Research, 23(3): 551–591

Cooke N J (2015). Team cognition as interaction. Current Directions in Psychological Science, 24(6): 415–419

Cooke N J, Gorman J C, Myers C W, Duran J L (2013). Interactive team cognition. Cognitive Science, 37(2): 255–285

Cooke N J, Gorman J C, Winner J L (2008). Team cognition. In: Durso F T, Nickerson R S, Dumais S T, Lewandowsky S, Perfect T J, eds. Handbook of Applied Cognition, 2nd ed. West Sussex: John Wiley & Sons

Cooke N J, Salas E E, Kiekel P A, Bell B (2005). Advances in measuring team cognition. In: Salas E, Fiore S M, eds. Team Cognition: Understanding the Factors that Drive Process and Performance, 83–106

Demir M, McNeese N J, Cooke N J (2017). Team situation awareness within the context of human-autonomy teaming. Cognitive Systems Research, 46: 3–12

Fang D, Chen Y, Wong L (2006). Safety climate in construction industry: A case study in Hong Kong. Journal of Construction Engineering and Management, 132(6): 573–584

Germain S (2015). Use of collaborative software to improve nuclear power plant outage management. In: International Topical Meeting on Nuclear Plant Instrumentation, Control, and Human Machine Interface Technologies. Charlotte, NC, US: Department of Energy Office of Nuclear Energy, 608–615

Germain S, Farris R K, Whaley A M, Medema H D, Gertman D I (2014). Guidelines for implementation of an advanced outage control center to improve outage coordination, problem resolution, and outage risk management. Technical Report. Idaho National Laboratory

Gorman J C, Cooke N J, Winner J L (2006). Measuring team situation awareness in decentralized command and control environments. Ergonomics, 49(12–13): 1312–1325

Gorman J C, Hessler E E, Amazeen P G, Cooke N J, Shope S M (2012). Dynamical analysis in real time: Detecting perturbations to team communication. Ergonomics, 55(8): 825–839

Hadavi S M H (2008). Risk-based, genetic algorithm approach to optimize outage maintenance schedule. Annals of Nuclear Energy, 35 (4): 601–609

Heo G, Park J (2010). A framework for evaluating the effects of maintenance-related human errors in nuclear power plants. Reliability Engineering and System Safety, 95(7): 797–805

Hu D, Mohamed Y (2010). State-based simulation mechanism for facilitating project schedule updating. In: Construction Research Congress 2010: Innovation for Reshaping Construction Practice, 369–378

Jan S H, Tserng H P, Ho S P (2013). Enhance construction visual as-built schedule management using BIM technology. International Journal of Civil Science and Engineering, 7(11): 812–817

Jang I, Ryum A, Ali M, Al S, Jun S, Gook H, Hyun P (2013). An empirical study on the basic human error probabilities for NPP advanced main control room operation using soft control. Nuclear Engineering and Design, 257: 79–87

Kim J, Park J (2012). Reduction of test and maintenance human errors by analyzing task characteristics and work conditions. Progress in Nuclear Energy, 58: 89–99

Kundakcı N, Kulak O (2016). Hybrid genetic algorithms for minimizing makespan in dynamic job shop scheduling problem. Computers & Industrial Engineering, 96: 31–51

Lee S H, Pena-Mora F (2005). System dynamics approach for error and change management in concurrent design and construction. In: Proceedings of the 37th Winter Simulation Conference. IEEE, 1508–1514

Liao P C, Lei G, Fang D, Liu W (2014). The relationship between communication and construction safety climate in China. KSCE Journal of Civil Engineering, 18(4): 887–897

Lloyd R L (2003). A survey of crane operating experience at US nuclear power plants from 1968 through 2002. Division of Systems Analysis and Regulatory Effectiveness, Office of Nuclear Regulatory Research, US Nuclear Regulatory Commission

Loftus G R (1985). Evaluating forgetting curves. Journal of Experimental Psychology: Learning, Memory, and Cognition, 11(2): 397–406

Love P E D, Li H (2000). Quantifying the causes and costs of rework in construction. Construction Management and Economics, 18(4):

479–490

Lu M (2003). Simplified discrete-event simulation approach for construction simulation. Journal of Construction Engineering and Management, 129(5): 537–546

McKendall A R, Noble J S, Klein C M (2008). Scheduling maintenance activities during planned outages at nuclear power plants. International Journal of Industrial Engineering: Theory, Applications and Practice, 15(1): 53–61

Neboyan V, Lederman L (1987). Human factors in the operation of nuclear power plants improving the way man and machines work together. International Atomic Energy Agency Bulletin, 29(4): 27–30

Nembhard D A (2000). The effects of task complexity and experience on learning and forgetting: A field study. Human Factors: The Journal of the Human Factors and Ergonomics Society, 42(2): 272–286

Nembhard D A, Bentefouet F (2012). Parallel system scheduling with general worker learning and forgetting. International Journal of Production Economics, 139(2): 533–542

Promsorn P, Soponsakulrat P, Adulyanukosol C, Kaiyarit P, Chinda T (2015). Identifying root causes of construction accidents: Non-human error factors. International Journal of Computing, Communications & Instrumentation Engineering, 2(1): 1–5

Pyy P (2001). An analysis of maintenance failures at a nuclear power plant. Reliability Engineering & System Safety, 72(3): 293–302

Rozinat A, Wynn M T, van der Aalst W M P, ter Hofstede A H M, Fidge C J (2009). Workflow simulation for operational decision support. Data and Knowledge Engineering, 68(9): 834–850

Sacks R, Perlman A, Barak R (2013). Construction safety training using immersive virtual reality. Construction Management and Economics, 31(9): 1005–1017

Sambasivan M, Soon Y W (2007). Causes and effects of delays in Malaysian construction industry. International Journal of Project Management, 25(5): 517–526

Scott M J, Guntuku S C, Huan Y, Lin W, Ghinea G (2015). Modelling human factors in perceptual multimedia quality: On the role of personality and culture. In: Proceedings of the 23rd ACM International Conference on Multimedia, 481–490

Seo J O, Lee S H, Seo J (2016). Simulation-based assessment of workers' muscle fatigue and its impact on construction operations. Journal of Construction Engineering and Management, 142(11): 04016012–04016063

Smart P R, Shadbolt N R (2012). Modelling the dynamics of team sensemaking: A constraint satisfaction approach. Knowledge Systems for Coalition Operations, 1–10

Sun Z, Zhang C, Tang P (2018a). Simulation-based optimization of communication protocols for reducing delays during nuclear power plant outages. In: Construction Research Congress 2018: Infrastructure and Facility Management, 455–464

Sun Z, Zhang C, Tang P, Wang Y, Liu Y (2018b). Bayesian network modeling of airport runway incursion occurring processes for predictive accident control. In: Advances in Informatics and Computing in Civil and Construction Engineering. Cham: Springer, 669–676

Techera U, Hallowell M, Littlejohn R, Rajendran S (2018). Measuring and predicting fatigue in construction: Empirical field study. Journal of Construction Engineering and Management, 144(8): 04018062

Von Eckardt B (1995). What Is Cognitive Science? Massachusetts: MIT Press

Von Eckardt B (2001). Multidisciplinarity and cognitive science. Cognitive Science, 25(3): 453–470

Wakker P H, Verhagen F C M, van Bloois J T, Sutton III W R (2003). Reducing refueling outage duration by optimizing core design and shuffling sequence. In: Advances in Nuclear Fuel Management III (ANFM 2003). Hilton Head Island, South Carolina, 1–16

Wang Y, Liu Y, Sun Z, Tang P (2018). A Bayesian-entropy network for information fusion and reliability assessment of national airspace systems. In: Proceeding of the 10th Annual Conference of the Prognostics and Health Management Society, 10(1)

Zhang C, Tang P, Cooke N, Buchanan V, Yilmaz A, Germain S, Boring R, Akca-Hobbins S, Gupta A (2017). Human-centered automation for resilient nuclear power plant outage control. Automation in Construction, 82: 179–192

Zhang C, Tang P, Yilmaz A, Cooke N, Chasey A, Jones S (2016). Automatic crane-related workflow control for nuclear plant outages through computer vision and simulation. In: Proceedings of the International Symposium on Automation and Robotics in Construction (ISARC). Auburn, AL: Department of Construction Economics & Property, Vilnius Gediminas Technical University

Zhang H, Tam G M, Shi J J (2002). Simulation-based methodology for project scheduling. Construction Management and Economics, 20 (8): 667–678

Zhang P, Li N, Jiang Z, Fang D, Anumba C J (2019). An agent-based modeling approach for understanding the effect of worker-management interactions on construction workers' safety-related behaviors. Automation in Construction, 97: 29–43