Available online at www.sciencedirect.com

ScienceDirect

International Journal of Project Management 34 (2016) 1393 – 1402

International Journal of Project Management

www.elsevier.com/locate/ijproman

Analysis of interacting uncertainties in on-site and off-site activities: Implications for hybrid construction

Mehrdad Arashpour [a,*], Ron Wakefield [a,1], E.W.M. Lee [b,2], Ricky Chan [c,3], M. Reza Hosseini [d,4]

[a] *School of Property, Construction and Project Management, RMIT University, 360 Swanston St, Melbourne, VIC 3000, Australia*
[b] *Department of Architecture and Civil Engineering, City University of Hong Kong, Kowloon, Hong Kong*
[c] *School of Civil, Environmental and Chemical Engineering, RMIT University, 360 Swanston St, Melbourne, VIC 3000, Australia*
[d] *School of Architecture and Built Environment, Deakin University, Deakin University, Geelong, VIC, Australia*

Received 23 June 2015; received in revised form 20 January 2016; accepted 1 February 2016
Available online 2 March 2016

Abstract

Interaction and integration of uncertainties in on-site and off-site project activities often result in the risk of delays and schedule overruns in hybrid construction projects. To address this problem, a holistic risk analysis approach that assesses the integrating impact of uncertainties on completion times is proposed. The results of the analysis show that growth in project size and work quantities intensifies pair and group interconnection of tasks within and between groups of on-site and off-site activities, resulting in lengthened completion times and deviations from project plans. Unavailability of resources, risk seeking attitudes, and workflow variability are other major contributors to the risk of late completion in hybrid construction. While project managers often analyze on-site and off-site uncertainties separately, practical implications of the research results suggest adoption of a holistic approach in which risk management practices in the two environments are integrated. This approach significantly improves tangible performance measures in projects.

Keywords: Decision making; Delay; Discrete event simulation; Integration; Performance measures; Prefabricated building elements; Project management; Resource availability; Workflow variance

1. Introduction

The effect of uncertainty is significant in hybrid construction projects where a combination of on-site and off-site activities is concurrently in progress (Blismas et al., 2010, Boyd et al., 2013). In hybrid construction projects, some structural elements such as foundations/footings and main columns are site-built. The remaining building components are prefabricated in the controlled environment of a factory and are shipped to the worksite for installation. This working arrangement in hybrid construction imposes risks, defined as the effect of uncertainty on project objectives (ISO31000, 2009). On-site project activities are often undertaken under uncertainty in weather conditions, quality of work, and safety (Loosemore and Andonakis, 2007). Similarly, there is uncertainty in off-site construction in availability of resources, compliance of the manufactured elements with on-site requirements, and equipment failure (Polat et al., 2006).

The interactions of above uncertainties in on-site and off-site construction result in risk of delays and lengthened completion times (Porwal et al., 2012, Lu and Yan, 2013). As an example, despite the fact that many on-site house building operations such as framing and building roof trusses have been shortened

* Corresponding author. Tel.: +613 99253513; fax: +613 99251939.
E-mail addresses: Mehrdad.arashpour@rmit.edu.au (M. Arashpour), ron.wakefield@rmit.edu.au (R. Wakefield), ericlee@cityu.edu.hk (E.W.M. Lee), ricky.chan@rmit.edu.au (R. Chan), reza.hosseini@deakin.edu.au (M.R. Hosseini).
[1] Tel.: +613 99253448.
[2] Tel.: +852 3442 2307.
[3] Tel.: +613 99259975.
[4] Tel.: +613 52272333.

http://dx.doi.org/10.1016/j.ijproman.2016.02.004
0263-7863/00/

by using off-site manufactured elements, the average house completion time in Australia has not decreased. Fig. 1 illustrates the increasing trend in house completion times for an average Australian suburban house in different states (Australian Bureau of Statistics, 2015).

Although the literature supports combined benefits of on-site and off-site construction in hybrid projects (Zika-Viktorsson et al., 2006, Yung and Yip, 2010; Meiling et al., 2012), combination and interaction of uncertainties in hybrid construction and implications for project planning remain overlooked areas of research (Jaillon and Poon, 2009).

In order to understand effects of uncertainty interactions in hybrid construction projects, this paper focuses on off-site and on-site construction activities. In particular, this study analyzes the effects of combined risks on project completion times. The paper consists of an extensive review of project risk analysis in the construction context and development of four propositions based on empirical research.

2. Research background

Growing complexity of projects has exposed them to interacting uncertainties that cannot be efficiently addressed by existing management methods (Fang et al., 2012, Gagarina et al., 2015, Marle, 2015). The interaction and integration of uncertainties in off and on-site construction result in risk of deviations from plans and late completion of hybrid projects (Krane et al., 2012). Effective modeling of interacting uncertainties needs to reflect the propagation behavior in the project risk network (Marle, 2012; Fang and Marle, 2015). As an example in hybrid construction projects, a structured process to analyze complex interactions between off-site and on-site project risks can significantly improve the performance of the classical methods of risk analysis (Zhang et al., 2014b).

2.1. Risk analysis in construction projects

The high failure rate of construction projects is a result of underestimating the extent of uncertainty and risk (Hwang et al., 2014). Construction projects are often considered risky as they are one-off enterprises with numerous stakeholders, entailing substantial interactions between internal and external environments (Zwikael et al., 2006, Mu et al., 2014). The reputation of construction industry in terms of risk analysis is not as good as other sectors such as insurance or finance. This stems from the traditional risk perception in the construction industry as an estimation variance rather than a major project attribute (Lehtiranta, 2014). Gradually, however, there has been a paradigm shift in construction towards systematic and more sophisticated risk management practices.

In terms of tools and techniques, additional dimensions have been added to the traditional probability–impact (P–I) model of risk analysis. These dimensions include but are not limited to the risk exposure extent (Jannadi and Almishari, 2003), risk manageability level (Aven et al., 2007, Chan et al., 2015), influence of the surrounding environment and interdependencies among risks (Zeng et al., 2007), and risk significance (Han, Kim et al., 2008). These added dimensions aim to improve the traditional P–I model to better analyze the interacting risks in increasingly complicated construction projects.

As can be seen in Fig. 2, risk modeling and analysis with all above mentioned improvements have been used to assess different risk problems in construction project management. The bidding price estimation for projects is a widely investigated risk-related problem in the construction literature (Paek et al., 1993, East et al., 2009, Abdul-Rahman et al., 2012). Furthermore, risk of cost and schedule overrun has been modeled and analyzed using a range of tools and techniques (Love et al., 2013, Shehu et al., 2014, Williams and Gong, 2014). Project risks have been quantitatively analyzed using monetary equivalents in order to

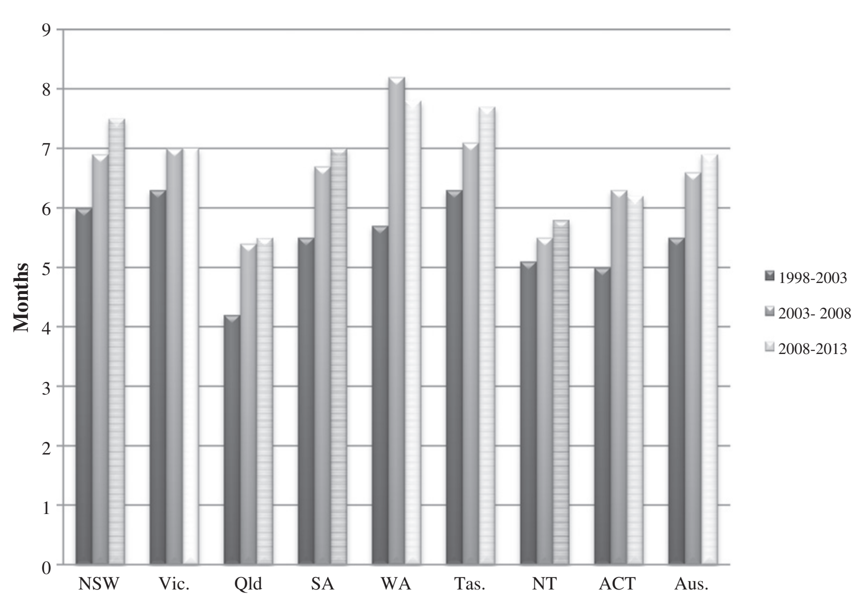

Fig. 1. House completion times in Australian states.

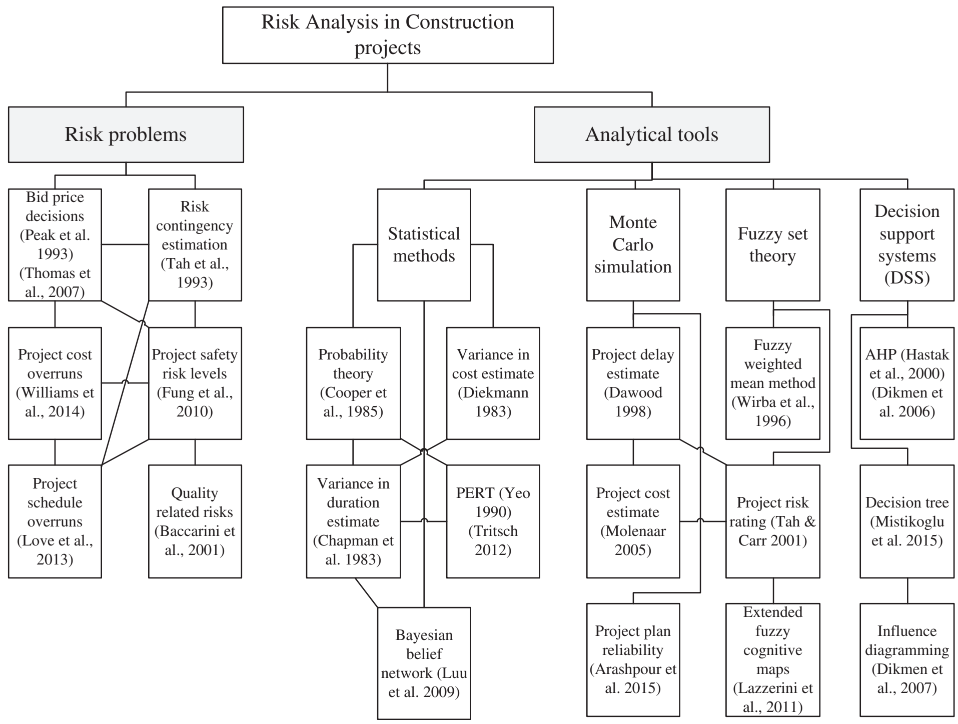

Fig. 2. Risk-related problems in construction and modeling paradigms to analyze risks.

estimate contingency budgets required for covering the expected cost of risk impacts (Tah et al., 1993, Cagno et al., 2007). Various modeling paradigms have been adopted to assess risk impacts on different project objectives including quality (Zhang et al., 2014b), time (Zwikael et al., 2014), and cost (Khodakarami and Abdi, 2014).

As illustrated in Fig. 2, statistical methods are one of the main tools used in project risk analysis. Many researchers have used the probability theory to analyze and assess risk problems (Cooper et al., 1985, Zhang et al., 2014a, Kim, 2015). This theory has been utilized to model different risk problems such as variance in cost estimate (Diekmann, 1983; Skitmore and Ng, 2002, Kim, Han et al., 2008), and variance in duration estimate (Lee and Diekmann, 2011; Hajifathalian et al., 2012). Project evaluation and review technique (PERT) also uses statistical analysis to tackle uncertainties in project duration (Trietsch and Baker, 2012; Hajdu, 2013). More recently, Bayesian belief network (BBN) has been increasingly used as a tool for risk modeling and analysis (Khodakarami and Abdi, 2014; Leu and Chang, 2015).

Monte Carlo simulation is another tool used to generate more accurate estimates in analyzing project risks. A variety of risk problems have been analyzed using simulation, including project time overruns (Hatmoko and Scott, 2010; Gurgun et al., 2013) and project cost overruns (Liu et al., 2011, Karakas et al., 2013). Recently, more sophisticated simulation models have been utilized to tackle complicated risk problems in construction such as computing the level of projects plan reliability (Rashki et al., 2014).

Fuzzy set theory (FST) is another powerful tool to model subjectivity in project risk management. FST is capable of analyzing risk elements and provide risk ratings by using linguistic variables to represent fuzzy sets associated with membership functions (Tah and Carr, 2000; Zeng et al., 2007, Nieto-Morote and Ruz-Vila, 2011). Among other risk analysis problems, tackling the interdependency and causality between risks is particularly difficult to solve. Extended fuzzy cognitive maps can be used for this purpose resulting in enhancement of decision making process in complex projects (Lazzerini and Mkrtchyan, 2011).

More recent attempts to model and analyze risks in complex projects has manifested in the development of sophisticated decision support systems (DSS). Complex decision making processes are structured systematically using a multi-criteria decision making (MCDM) framework (Cagno et al., 2001, Marques et al., 2011). Analytical hierarchy process (AHP) is another widely used approach to accommodate the decision maker's personal judgment in prioritizing decision alternatives (Mahdi and Alreshaid, 2005; Vidal et al., 2011). Decision trees and influence diagramming are also used within the MCDM framework to analyze complicated risk problems in construction projects (Dikmen et al., 2007, Mistikoglu et al., 2015).

Overall, the use and development of modern risk analysis tools and techniques in construction risk management reflect the shift from the traditional risk perception in the construction industry as an estimation variance to a major project attribute. The framework for the empirical research in this paper is described in the following section.

3. Research method

3.1. Empirical research

In this article, empirical research is conducted in order to analyze the impact of uncertainty in hybrid construction projects, where combinations of on-site and off-site activities are concurrently in progress. Real-world project data from two case studies were collected and utilized to design and run simulation experiments with various levels of work quantities, targeted project plan reliability, resource availability, and workflow variance.

The utilization of simulation modeling is ideal in this research as both on-site and off-site project activities are stochastic and dynamic in nature, and changes within activities occur as a variable of time. Furthermore, the advancement of computers simulation and modeling has provided an economical and efficient mean for optimization of project activities (Dzeng and Lee, 2007; Chou, 2011). Within the project management context, simulation study has been treated as an effective and popular method for exploring, describing and interpreting processes or behaviours in construction projects.

As defined by Shi et al. (2005), simulation study encompasses exploring a number of what-if scenarios confined by activity and time boundaries for collecting comprehensive information during a certain period of time. To this end, off-site and on-site construction activities in two large Australian construction companies were investigated. Both companies own off-site production plants and use industrialized building components together with site-built structural elements in their commercial construction developments. Required data for conducting this research were collected during numerous observations of on-site and off-site construction activities. The main variables that characterize uncertainty in hybrid projects were measured: 1) size of project and quantities of work involved, 2) targeted level of plan reliability that reflects the attitude in project towards uncertainties, 3) variability caused by unavailability of required resources in either off-site or on-site activities, and 4) workflow variability in the interdependent networks of off-site and on-site activities.

Various modeling paradigms have been adopted in the literature to assess risk impacts on different project objectives. In order to analyze the collected data in the current research, Monte Carlo simulation was deemed suitable for use because of its potential in tackling complicated risk problems in hybrid construction and power to analyze what-if scenarios in complex environments (Dzeng and Lee, 2007; Chou, 2011; Yang et al., 2014). The framework of the DES experiments designed to model processes in hybrid construction projects of the two companies is described in the following section.

3.2. Experimental framework

Detailed data about off-site and on-site construction activities together with project progress data for the two construction companies were collected and optimal probability distributions were fitted to them. In each case, goodness of fit tests in the @ Risk probability distribution fitting software were used to evaluate the fit quality. Fig. 3 illustrates examples of best fitted distributions for a number of on-site and off-site activities.

In a similar approach to Akhavian and Behzadan (2014), the goodness of fit was tested using Chi-Square test, Anderson–Darling (A–D) test, and Kolmogorov–Smirnov (K–S) test. Table 1 shows some commonly used standard theoretical probability distributions receiving the highest rank amongst all distributions to represent processing times of two example activities in simulation experiments. The term N/A under a statistical distribution indicates the failure of data convergence and the fact that collected data could not be fitted to a particular distribution.

After fitting activity durations in the two hybrid construction projects to best-matching probability distributions, simulation experiments analyzed different production scenarios by varying:

- w — work quantities (man-hours) involved in the hybrid construction project
- PPR — project plan reliability (how often completions are on time or earlier than planned)
- A — level of resource availability in the hybrid project (ranging from 100% for dedicated resources to 0%)
- v — variability/uncertainty level in off-site and on-site activities (standard deviation of time between activity completions)

A total of 16,000 discrete event simulation experiments were designed and run by using combinations of 20 different project work quantities, eight levels of targeted project plan reliability, 10 resource availability levels, and 10 levels of workflow variance in project activities. Results of analyzing different what-if scenarios were utilized to derive four propositions of this paper about uncertainty impacts on hybrid construction projects.

4. Discussion of results

4.1. Effects of project size in hybrid construction projects

Previous research has highlighted the relationship between project size and uncertainty in projects (Pollack et al., 2013, Saurin et al., 2013, Qureshi and Kang, 2015). In order to examine this relationship in the context of hybrid construction, real-world project data from two hybrid builders were utilized to design simulation experiments with various levels of work quantities. As opposed to the traditional planning and control techniques such as PERT, using only normal/beta distributions, in this study uncertainty in activity durations and workflow was reflected by fitting optimum probability distributions to the collected real-world data (see Fig. 3). The goodness of fit was tested using Chi-Square test, Anderson–Darling (A–D) test, and Kolmogorov–Smirnov (K–S) test. Discrete event simulation (DES) experiments were run for 1000 times to achieve a confidence level of 99% with all standard errors within 0.5%. Results of simulation experiments have been illustrated in Fig. 4.

As can be seen in Fig. 4, increasing project work quantities (w) resulted in a linear growth in completion times. This is in line with findings in our site observations in the two construction companies where growth in hybrid project size and work quantities, intensified pair and group interconnection of tasks within and between groups of on-site and off-site activities, resulting in lengthened completion times and deviations from project plans. As an example, the first construction company

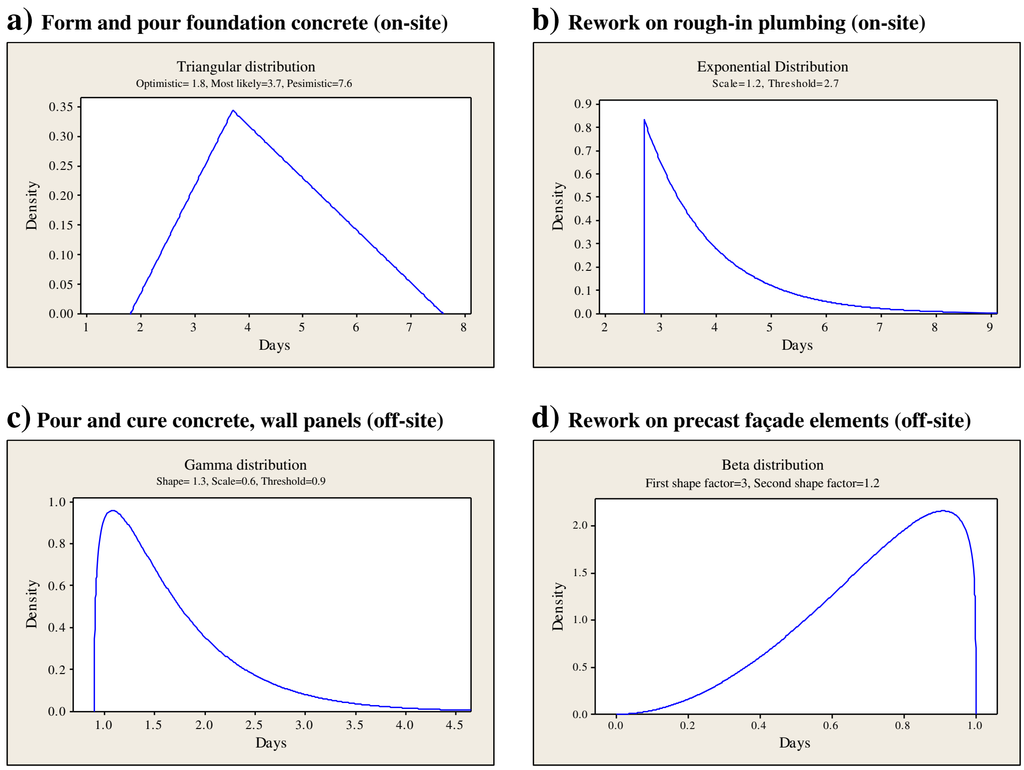

Fig. 3. Probability distributions of some on-site and off-site activities.

invested 80 man-hours on 120 m^2 roofing activities for a detached residential unit. The amount of work was inflated to 210 man-hours for the second company installing seamless roofing material and spreading stone ballast on seamless roof in a big 2-storey house.

It is worth mentioning that the standard practice of fast-tracking project activities will not significantly reduce completion times, as there are many construction activities with fixed-time durations, such as pouring and curing concrete, which cannot be crashed beyond a certain point. That is why actual/reliable completion time (dashed line in Fig. 4) is always longer than estimated completion time (vertical bars). More importantly, time gap between the two is greater when larger work quantities (w) are involved. These findings are consistent with those of Martinsuo and Ahola (2010); Pauget and Wald (2013) and Ahern et al. (2014), and result in the advancement of the first proposition in this paper,

Proposition 1. In hybrid construction projects, growth in off-site and/or on-site work quantities increases the risk of deviations from project plan and reduces project plan reliability.

4.2. Effects of organization's risk appetite in hybrid construction projects

Construction projects are often characterized by their very dynamic environments where actual progress is not always aligned with project plans. In hybrid projects risk of late completions and deviations from plans are triggered by delays in both on-site and off-site activities. Bad weather conditions (Chan and Au, 2007), quality problems and rework (Arashpour et al., 2014a, 2014b), and worksite accidents (Lingard et al., 2014) are some contributors to delays in on-site activities. Similarly, several factors can trigger the risk of late completion in off-site construction. These factors include but are not

Table 1
Ranking of the best-matching probability distributions to real-world processing times.

	Test	Exponential	Triangular	Gamma	Beta	Erlang	Normal
	Chi-Square	5	1	4	2	N/A	3
Form & pour foundation concrete (on-site)	K–S	4	3	5	1	N/A	2
	A–D	1	3	2	5	N/A	4
Rank		10	7	11	8	N/A	9
	Chi-Square	1	3	2	4	6	5
Rework on precast façade elements (off-site)	K–S	5	3	4	1	6	2
	A–D	5	2	6	1	4	3
Rank		11	8	12	6	16	10

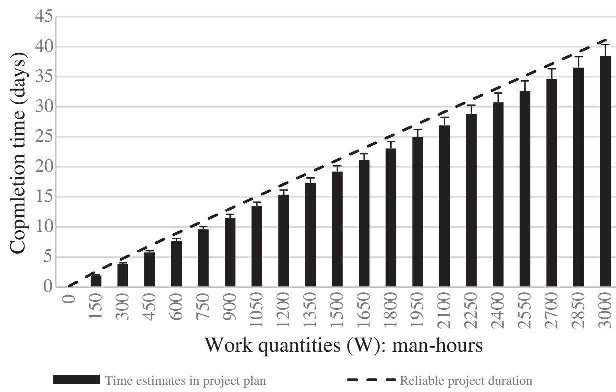

Fig. 4. Impact of work quantities and project size on completion times.

limited to unavailability of resources (Blismas et al., 2006, Lee et al., 2013), lack of compliance of the manufactured elements with on-site requirements (Arashpour and Arashpour, 2015), and equipment failure (Polat et al., 2006).

Furthermore, risk attitudes in hybrid projects have an impact on the level of plan reliability. The two investigated hybrid builders in this study demonstrated different appetite for project risks. Company (B) is a young enterprise, seeking a larger market share, and has been historically more willing to absorb the impact of various risks such as late completion risk (with an average on-time completion rate of 87%). Company (A), however, is a more established enterprise and already has a major share of the market. This company intends to be very risk averse and as an example has increased its targeted level of project plan reliability to minimize the risk of late completions (with an average on-time completion rate of 94%). Fig. 5 illustrates the completion time for one project milestone against different levels of targeted plan reliability.

Results in Fig. 5 clearly show that risk aversion behavior in hybrid projects results in more conservative plans that tend to increase both completion times and reliability. This result is in line with those of Castro-Lacouture et al. (2009) and Poshdar et al. (2014), and the following propositions can be derived from that,

Proposition 2a. Targeted level of project plan reliability in hybrid construction projects is determined by organization's appetite for risk.

Proposition 2b. Risk of late completions in hybrid construction projects decreases when the level of targeted project plan reliability increases.

4.3. Effects of resource availability in hybrid construction projects

Previous research has shown that resource constraints have a significant impact on project duration (Shi et al., 2005, Bredillet, 2008; Ghoddousi et al., 2013). In hybrid projects, there are different constraints on project resources in on-site and off-site environments. In off-site construction, equipment and materials are the critical resources based on the fact that laborers (machine operators) are often dedicated resources to the production side of hybrid projects (Arashpour et al., 2014a, 2014b). In on-site project activities, however, subcontractors and skilled labor are the most critical resources to achieve timely completions (Loosemore and Andonakis, 2007; Tam et al., 2011, Manu et al., 2013). Interestingly, even within a construction company with more than one ongoing project, there is often competition among building supervisors to attract in-demand resources, such as skilled carpenters, to their own project (Laslo and Goldberg, 2008).

Both site observations and simulation experiments revealed that the level of resource availability has a significant impact on completion times of on-site and off-site project activities. Fig. 6 illustrates the actual completion times associated with different levels of resource availability.

As Fig. 6 illustrates, availability of required resources decreases completion time, and thus reduces risk of deviations from project plan, because resource availability increases the workflow continuity in hybrid projects. In other words, relaxation of resource constraints in hybrid projects can reduce risk of late completions and low plan reliability. This is consistent with findings of Zhao et al. (2010) and Arashpour et al. (2015a, 2015b), and results in advancement of the third proposition of the paper,

Proposition 3. Completion times in hybrid construction projects are inflated nonlinearly as a result of resource scarcity. The increase in completion time is significant when resource availability levels drop below 50%.

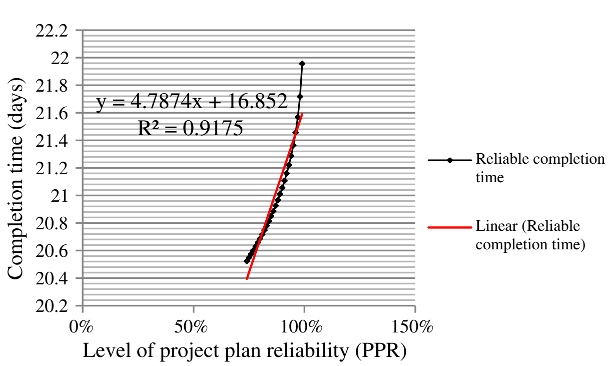

Fig. 5. Impact of plan reliability on completion times.

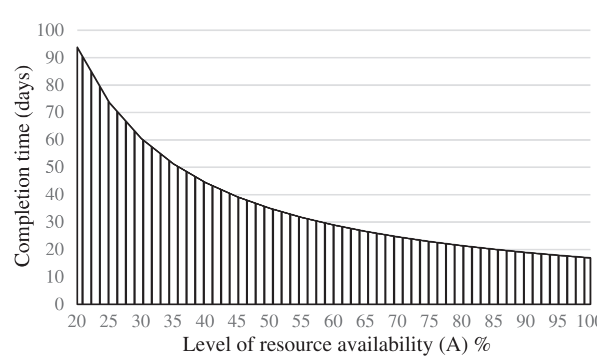

Fig. 6. Impact of resource availability on completion times in the hybrid project.

4.4. Combined uncertainty in off-site and on-site operations

In hybrid projects, off-site constructed elements are transferred to the worksite to be installed. Although off-site construction of building components in the controlled environment of a manufacturing plant results in time savings (Pan et al., 2012), dimensional and specification anomalies can impose risk of rework and delays on hybrid construction projects (Arashpour et al., 2015a, 2015b). When an off-site constructed building element does not comply with on-site requirements, it is sent back to the production plant to be modified or scrapped. As a result, the hybrid project is delayed. Off-site activities are not the only source of uncertainty in hybrid projects as the interaction of uncertainties in off-site and on-site operations is always a two-way street. For example, if on-site operations are running behind schedule and off-site constructed elements are not installed according to the schedule, a large inventory of products is created in the manufacturing plant resulting in congestion at the off-site production side of the hybrid project.

Discrete event simulation (DES) experiments modeled different what-if scenarios with various combinations of on-site and off-site workflow variability. Resultant completion times were recorded against the level of combined variability (standard deviation of time between activity completions). As can be seen in Fig. 7, increasing the level of uncertainty in hybrid projects results in longer completion times and a risk of deviations from project plans (reduced plan reliability).

As Fig. 7 illustrates, low variability levels in hybrid projects result in improved workflow continuity and shorter completion times. Some on-site construction activities such as concreting and off-site activities such as making window frames with long lead procurements are prone to high levels of variability, leading hybrid projects towards deviations from plans and late completions. It should be noted that to achieve a low variability level, combined uncertainties in both off-site and on-site activities should be minimized. High levels of combined uncertainties in projects result in lengthened durations, triggering the risk of plan infeasibility. This finding is in line with those of Xu et al. (2012), Arashpour et al. (2013), (Acebes et al. (2014) and Arashpour et al. (2016), and leads to the final proposition of this research,

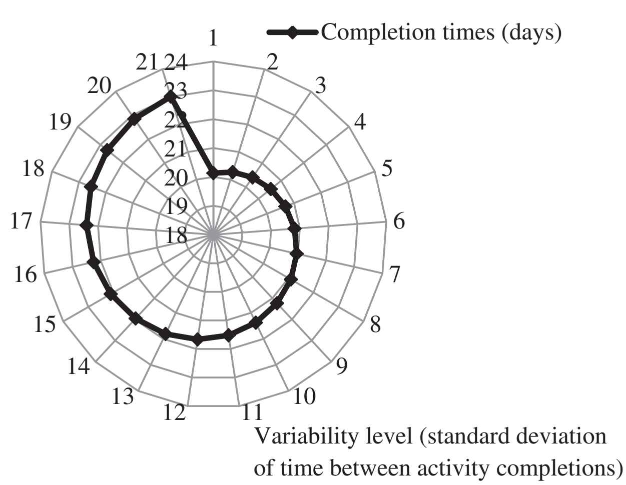

Fig. 7. Interaction of workflow variability (v) and completion times in hybrid construction.

Proposition 4. Risk of late completion and deviations from project plans decreases by reducing the combined level of workflow variability (v) in on-site and off-site project activities.

The final proposition indicates that off-site production and on-site activities are interconnected and thus the uncertainties in hybrid construction projects should be managed in an integrative manner.

5. Conclusions

This paper has shed light on dynamics of risk and uncertainty in hybrid construction projects. It suggests that risk of late completion in these projects intensifies as a result of uncertainty combination in off-site and on-site construction. Project size and work quantities, organization's risk appetite, resource availability, and workflow variability are contributors to the risk of late completion in hybrid construction projects. This paper contributes to theory by developing four robust propositions explaining the impact of interacting uncertainty on project completion time in hybrid construction.

Practical contribution of this research targets project managers and senior executives. While project managers tend to analyze and manage on-site and off-site risks separately, hybrid construction projects may benefit from integrating risk management practices in the two environments. Senior executives can ensure sufficient resources are available to both off-site production and on-site activities, considering the level of workflow variability. This significantly reduces the risk of late completions in hybrid construction projects.

Finally, limitations of this research should be noted. Due to limited access to hybrid project data, four variables were selected to investigate uncertainty in project completion times. For greater generalizability of the research conclusions, future research should use more variables and bigger sample sizes to analyze the effects of uncertainty in hybrid projects.

Conflict of interest

There is no conflict of interest.

Acknowledgements

The authors would like to thank Professor Derek Walker for his constructive comments about this research. The authors would also like to acknowledge the support of Monarch Building Systems and Hickory Construction. Any opinions, findings, conclusions, and recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the companies or the individuals named above.

Appendix A. Notation and symbols

σ	Standard deviation of time between activity completions
A	Availability level for different resources
A–D	Anderson–Darling test for goodness of fit
DES	Discrete Event Simulation
K–S	Kolmogorov–Smirnov test for goodness of fit
PPR	Project Plan Reliability
w	Work quantities
v	Variability level

References

Abdul-Rahman, H., Wang, C., Malay, S.B., 2012. Structured project learning model toward improved competitiveness in bidding for large construction firms. J. Civ. Eng. Manag. 18 (4), 546–556.

Acebes, F., Pajares, J., Galán, J.M., López-Paredes, A., 2014. A new approach for project control under uncertainty. Going back to the basics. Int. J. Proj. Manag. 32 (3), 423–434.

Ahern, T., Leavy, B., Byrne, P.J., 2014. Complex project management as complex problem solving: a distributed knowledge management perspective. Int. J. Proj. Manag. 32 (8), 1371–1381.

Akhavian, R., Behzadan, A.H., 2014. Evaluation of queuing systems for knowledge-based simulation of construction processes. Autom. Constr. 47, 37–49.

Arashpour, M., Arashpour, M., 2015. Analysis of workflow variability and its impacts on productivity and performance in construction of multistory buildings. J. Manag. Eng. 040150061.

Arashpour, M., Wakefield, R., Blismas, N., Lee, E.W.M., 2013. A new approach for modelling variability in residential construction projects. Construction Econ. Build. 13 (2), 83–92.

Arashpour, M., Wakefield, R., Blismas, N., Lee, E.W.M., 2014a. Analysis of disruptions caused by construction field rework on productivity in residential projects. J. Constr. Eng. Manag. 140 (2), 04013053.

Arashpour, M., Wakefield, R., Blismas, N., Lee, E.W.M., 2014b. Framework for improving workflow stability: deployment of optimized capacity buffers in a synchronized construction production. Can. J. Civ. Eng. 41 (12), 995–1004.

Arashpour, M., Wakefield, R., Blismas, N., Maqsood, T., 2015a. Autonomous production tracking for augmenting output in off-site construction. Autom. Constr. 53, 13–21.

Arashpour, M., Wakefield, R., Blismas, N., Minas, J., 2015b. Optimization of process integration and multi-skilled resource utilization in off-site construction. Autom. Constr. 50 (1), 72–80.

Arashpour, M., Wakefield, R., Blismas, N., Abbasi, B., 2016. Quantitative analysis of rate-driven and due date-driven construction: Production efficiency, supervision, and controllability in residential projects. J. Constr. Eng. Manag. 142 (1), 04015006.

Australian Bureau of Statistics, 2015. Construction Work Done in Australia (8755.0).

Aven, T., Vinnem, J.E., Wiencke, H.S., 2007. A decision framework for risk management, with application to the offshore oil and gas industry. Reliab. Eng. Syst. Saf. 92 (4), 433–448.

Blismas, N., Pasquire, C., Gibb, A., 2006. Benefit evaluation for off-site production in construction. Construction Manage. Econ. 24 (2), 121–130.

Blismas, N., Wakefield, R., Hauser, B., 2010. Concrete prefabricated housing via advances in systems technologies: development of a technology roadmap. Eng. Constr. Archit. Manag. 17 (1), 99–110.

Boyd, N., Khalfan, M.M.A., Maqsood, T., 2013. Off-site construction of apartment buildings. J. Archit. Eng. 19 (1), 51–57.

Bredillet, C.N., 2008. Learning and acting in project situations through a meta-method (MAP) a case study: contextual and situational approach for project management governance in management education. Int. J. Proj. Manag. 26 (3), 238–250.

Cagno, E., Caron, F., Perego, A., 2001. Multi-criteria assessment of the probability of winning in the competitive bidding process. Int. J. Proj. Manag. 19 (6), 313–324.

Cagno, E., Caron, F., Mancini, M., 2007. A multi-dimensional analysis of major risks in complex projects. Risk Manage. 9 (1), 1–18.

Castro-Lacouture, D., Süer, G.A., Gonzalez-Joaqui, J., Yates, J.K., 2009. Construction project scheduling with time, cost, and material restrictions using fuzzy mathematical models and critical path method. J. Constr. Eng. Manag. 135 (10), 1096–1104.

Chan, E.H.W., Au, M.C.Y., 2007. Building contractors' behavioural pattern in pricing weather risks. Int. J. Proj. Manag. 25 (6), 615–626.

Chan, R.W.K., Yuen, J.K.K., Lee, E.W.M., Arashpour, M., 2015. Application of nonlinear-autoregressive-exogenous model to predict the hysteretic behaviour of passive control systems. Eng. Struct. 85 (1), 1–10.

Chou, J.S., 2011. Cost simulation in an item-based project involving construction engineering and management. Int. J. Proj. Manag. 29 (6), 706–717.

Cooper, D., MacDonald, D., Chapman, C., 1985. Risk analysis of a construction cost estimate. Int. J. Proj. Manag. 3 (3), 141–149.

Diekmann, J.E., 1983. Probabilistic estimating: mathematics and applications. J. Constr. Eng. Manag. 109 (3), 297–308.

Dikmen, I., Birgonul, M.T., Gur, A.K., 2007. A case-based decision support tool for bid mark-up estimation of international construction projects. Autom. Constr. 17 (1), 30–44.

Dzeng, R.J., Lee, H.Y., 2007. Optimizing the development schedule of resort projects by integrating simulation and genetic algorithm. Int. J. Proj. Manag. 25 (5), 506–516.

East, E.W., Martinez, J.C., Kirby, J.G., 2009. Discrete-event simulation based performance quantification of web-based and traditional bidder inquiry processes. Autom. Constr. 18 (2), 109–117.

Fang, C., Marle, F., 2015. A framework for the modeling and management of project risks and risk interactions. Handbook on Project Management and Scheduling 2. Springer International Publishing, pp. 1105–1117.

Fang, C., Marle, F., Zio, E., Bocquet, J.C., 2012. Network theory-based analysis of risk interactions in large engineering projects. Reliab. Eng. Syst. Saf. 106, 1–10.

Gagarina, L.G., Kavtaradze, D.N., Mordovin, A.A., Portnov, E.M., Slyusar, V.V., Ye, K.Z., 2015. Modeling of a dynamic interaction of motor transport and natural systems in order to minimize the risks of project and management decisions. J. Comput. Sci. 11 (2), 297–303.

Ghoddousi, P., Eshtehardian, E., Jooybanpour, S., Javanmardi, A., 2013. Multi-mode resource-constrained discrete time–cost-resource optimization in project scheduling using non-dominated sorting genetic algorithm. Autom. Constr. 30, 216–227.

Gurgun, A.P., Zhang, Y., Touran, A., 2013. Schedule contingency analysis for transit projects using a simulation approach. J. Civ. Eng. Manag. 19 (4), 465–475.

Hajdu, M., 2013. Effects of the application of activity calendars on the distribution of project duration in PERT networks. Autom. Constr. (0).

Hajifathalian, K., Wambeke, B.W., Liu, M., Hsiang, S.M., 2012. Effects of production control strategy and duration variance on productivity and work in process: simulation-based investigation. J. Constr. Eng. Manag. 138 (9), 1035–1043.

Han, S.H., Kim, D.Y., Kim, H., Jang, W.S., 2008. A web-based integrated system for international project risk management. Autom. Constr. 17 (3), 342–356.

Hatmoko, J.U.D., Scott, S., 2010. Simulating the impact of supply chain management practice on the performance of medium-sized building projects. Construction Manage. Econ. 28 (1), 35–49.

Hwang, B.-G., Zhao, X., Toh, L.P., 2014. Risk management in small construction projects in Singapore: status, barriers and impact. Int. J. Proj. Manag. 32 (1), 116–124.

ISO31000, 2009. Risk Management—Principles and Guidelines. International Organization for Standardization, Geneva, Switzerland.

Jaillon, L., Poon, C.S., 2009. The evolution of prefabricated residential building systems in Hong Kong: a review of the public and the private sector. Autom. Constr. 18 (3), 239–248.

Jannadi, O.A., Almishari, S., 2003. Risk assessment in construction. J. Constr. Eng. Manag. 129 (5), 492–500.

Karakas, K., Dikmen, I., Birgonul, M.T., 2013. Multiagent system to simulate risk-allocation and cost-sharing processes in construction projects. J. Comput. Civ. Eng. 27 (3), 307–319.

Khodakarami, V., Abdi, A., 2014. Project cost risk analysis: a Bayesian networks approach for modeling dependencies between cost items. Int. J. Proj. Manag. 32 (7), 1233–1245.

Kim, B., 2015. Integrating risk assessment and actual performance for probabilistic project cost forecasting: a second moment Bayesian model. IEEE Trans. Eng. Manag.

Kim, D.Y., Han, S.H., Kim, H., 2008. Discriminant analysis for predicting ranges of cost variance in international construction projects. J. Constr. Eng. Manag. 134 (6), 398–410.

Krane, H.P., Olsson, N.O.E., Rolstadås, A., 2012. How project manager–project owner interaction can work within and influence project risk management. Proj. Manag. J. 43 (2), 54–67.

Laslo, Z., Goldberg, A.I., 2008. Resource allocation under uncertainty in a multi-project matrix environment: is organizational conflict inevitable? Int. J. Proj. Manag. 26 (8), 773–788.

Lazzerini, B., Mkrtchyan, L., 2011. Analyzing risk impact factors using extended fuzzy cognitive maps. IEEE Syst. J. 5 (2), 288–297.

Lee, J.S., Diekmann, J.E., 2011. Delay analysis considering production rate. Can. J. Civ. Eng. 38 (2), 361–372.

Lee, E.W.M., Fung, I.W.H., Tam, V.W.Y., Arashpour, M., 2013. A fully autonomous kernel-based online learning neural network model and its application to building cooling load prediction. Soft. Comput. 1–16.

Lehtiranta, L., 2014. Risk perceptions and approaches in multi-organizations: A research review 2000–2012. Int. J. Proj. Manag. 32 (4), 640–653.

Leu, S.-S., Chang, C.-M., 2015. Bayesian-network-based fall risk evaluation of steel construction projects by fault tree transformation. J. Civ. Eng. Manag. 21 (3), 334–342.

Lingard, H., Pirzadeh, P., Blismas, N., Wakefield, R., Kleiner, B., 2014. Exploring the link between early constructor involvement in project decision-making and the efficacy of health and safety risk control. Construction Manage. Econ. 32 (9), 918–931.

Liu, X., Wang, Z.F., Jin, D.Z., 2011. Risk evaluation of cost for hydropower construction under risk fixed schedule probability using monte carlo simulation method. Technics Technol. Educ. Manage. 6 (2), 287–299.

Loosemore, M., Andonakis, N., 2007. Barriers to implementing OHS reforms—the experiences of small subcontractors in the Australian construction industry. Int. J. Proj. Manag. 25 (6), 579–588.

Love, P.E.D., Sing, C.P., Wang, X., Edwards, D.J., Odeyinka, H., 2013. Probability distribution fitting of schedule overruns in construction projects. J. Oper. Res. Soc. 64 (8), 1231–1247.

Lu, S., Yan, H., 2013. A comparative study of the measurements of perceived risk among contractors in China. Int. J. Proj. Manag. 31 (2), 307–312.

Mahdi, I.M., Alreshaid, K., 2005. Decision support system for selecting the proper project delivery method using analytical hierarchy process (AHP). Int. J. Proj. Manag. 23 (7), 564–572.

Manu, P., Ankrah, N., Proverbs, D., Suresh, S., 2013. Mitigating the health and safety influence of subcontracting in construction: the approach of main contractors. Int. J. Proj. Manag. 31 (7), 1017–1026.

Marle, F., 2012. Considering interactions between risks in a large contract-based project. 11th International Probabilistic Safety Assessment and Management Conference and the Annual European Safety and Reliability Conference 2012. PSAM11 ESREL 2012, Helsinki.

Marle, F., 2015. A structured process to managing complex interactions between project risks. Int. J. Proj. Organ. Manag. 6 (1–2), 4–32.

Marques, G., Gourc, D., Lauras, M., 2011. Multi-criteria performance analysis for decision making in project management. Int. J. Proj. Manag. 29 (8), 1057–1069.

Martinsuo, M., Ahola, T., 2010. Supplier integration in complex delivery projects: comparison between different buyer–supplier relationships. Int. J. Proj. Manag. 28 (2), 107–116.

Meiling, J., Backlund, F., Johnsson, H., 2012. Managing for continuous improvement in off-site construction: evaluation of lean management principles. Eng. Constr. Archit. Manag. 19 (2), 141–158.

Mistikoglu, G., Gerek, I.H., Erdis, E., Mumtaz Usmen, P.E., Cakan, H., Kazan, E.E., 2015. Decision tree analysis of construction fall accidents involving roofers. Expert Syst. Appl. 42 (4), 2256–2263.

Mu, S., Cheng, H., Chohr, M., Peng, W., 2014. Assessing risk management capability of contractors in subway projects in mainland China. Int. J. Proj. Manag. 32 (3), 452–460.

Nieto-Morote, A., Ruz-Vila, F., 2011. A fuzzy approach to construction project risk assessment. Int. J. Proj. Manag. 29 (2), 220–231.

Paek, J.H., Lee, Y.W., Ock, J.H., 1993. Pricing construction risk: fuzzy set application. J. Constr. Eng. Manag. 119 (4), 743–756.

Pan, W., Gibb, A.G.F., Dainty, A.R.J., 2012. Strategies for integrating the use of off-site production technologies in house building. J. Constr. Eng. Manag. 138 (11), 1331–1340.

Pauget, B., Wald, A., 2013. Relational competence in complex temporary organizations: the case of a French hospital construction project network. Int. J. Proj. Manag. 31 (2), 200–211.

Polat, G., Arditi, D., Ballard, G., Mungen, U., 2006. Economics of on-site vs. off-site fabrication of rebar. Construction Manage. Econ. 24 (11), 1185–1198.

Pollack, J., Costello, K., Sankaran, S., 2013. Applying Actor-Network Theory as a sensemaking framework for complex organisational change programs. Int. J. Proj. Manag. 31 (8), 1118–1128.

Porwal, V., Dave, B., Fernandez-Solis, J., Koskela, L.J., Mehta, H.S., 2012. State of production plan reliability—a case study from India. 20th Conference of the International Group for Lean Construction, IGLC 2012, San Diego, CA.

Poshdar, M., González, V.A., Raftery, G.M., Orozco, F., 2014. Characterization of process variability in construction. J. Constr. Eng. Manag. 140 (11).

Qureshi, S.M., Kang, C., 2015. Analysing the organizational factors of project complexity using structural equation modelling. Int. J. Proj. Manag. 33 (1), 165–176.

Rashki, M., Miri, M., Moghaddam, M.A., 2014. A simulation-based method for reliability based design optimization problems with highly nonlinear constraints. Autom. Constr. 47 (0), 24–36.

Saurin, T.A., Rooke, J., Koskela, L., 2013. A complex systems theory perspective of lean production. Int. J. Prod. Res.

Shehu, Z., Endut, I.R., Akintoye, A., Holt, G.D., 2014. Cost overrun in the Malaysian construction industry projects: a deeper insight. Int. J. Proj. Manag. 32 (8), 1471–1480.

Shi, J.J., Li, H., Zhang, H., 2005. Two resource dispatching rules for modeling human decisions in simulation. Int. J. Proj. Manag. 23 (2), 97–107.

Skitmore, M., Ng, S.T., 2002. Analytical and approximate variance of total project cost. J. Constr. Eng. Manag. 128 (5), 456–460.

Tah, J.H.M., Carr, V., 2000. A proposal for construction project risk assessment using fuzzy logic. Construction Manage. Econ. 18 (4), 491–500.

Tah, J.H.M., Thorpe, A., McCaffer, R., 1993. Contractor project risks contingency allocation using linguistic approximation. Comput. Syst. Eng. 4 (2–3), 281–293.

Tam, V.W.Y., Shen, L.Y., Kong, J.S.Y., 2011. Impacts of multi-layer chain subcontracting on project management performance. Int. J. Proj. Manag. 29 (1), 108–116.

Trietsch, D., Baker, K.R., 2012. PERT 21: fitting PERT/CPM for use in the 21st century. Int. J. Proj. Manag. 30 (4), 490–502.

Vidal, L.A., Marle, F., Bocquet, J.C., 2011. Measuring project complexity using the analytic hierarchy process. Int. J. Proj. Manag. 29 (6), 718–727.

Williams, T.P., Gong, J., 2014. Predicting construction cost overruns using text mining, numerical data and ensemble classifiers. Autom. Constr. 43, 23–29.

Xu, J., Zheng, H., Zeng, Z., Wu, S., Shen, M., 2012. Discrete time–cost–environment trade-off problem for large-scale construction systems with multiple modes under fuzzy uncertainty and its application to Jinping-II Hydroelectric Project. Int. J. Proj. Manag. 30 (8), 950–966.

Yang, Q., Lu, T., Yao, T., Zhang, B., 2014. The impact of uncertainty and ambiguity related to iteration and overlapping on schedule of product development projects. Int. J. Proj. Manag. 32 (5), 827–837.

Yung, P., Yip, B., 2010. Construction quality in China during transition: a review of literature and empirical examination. Int. J. Proj. Manag. 28 (1), 79–91.

Zeng, J., An, M., Smith, N.J., 2007. Application of a fuzzy based decision making methodology to construction project risk assessment. Int. J. Proj. Manag. 25 (6), 589–600.

Zhang, S., Nishijima, K., Maruyama, T., 2014a. Climate model-based probabilistic assessment of wind risk for residential buildings under projected future climate. Civ. Eng. Environ. Syst. 31 (2), 98–110.

Zhang, L., Wu, X., Skibniewski, M.J., Zhong, J., 2014b. Dynamic risk assessment in construction projects using Bayesian networks. 31st International Symposium on Automation and Robotics in Construction and Mining, ISARC 2014. University of Technology, Sydney.

Zhao, Z., You, W., Zuo, J., 2010. Application of innovative critical chain method for project planning and control under resource constraints and uncertainty. J. Constr. Eng. Manag. 136 (9), 1056–1060.

Zika-Viktorsson, A., Sundström, P., Engwall, M., 2006. Project overload: an exploratory study of work and management in multi-project settings. Int. J. Proj. Manag. 24 (5), 385–394.

Zwikael, O., Cohen, Y., Sadeh, A., 2006. Non-delay scheduling as a managerial approach for managing projects. Int. J. Proj. Manag. 24 (4), 330–336.

Zwikael, O., Pathak, R.D., Singh, G., Ahmed, S., 2014. The moderating effect of risk on the relationship between planning and success. Int. J. Proj. Manag. 32 (3), 435–441.