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Integrated management of on-site, coordination and off-site uncertainty: Theorizing risk analysis within a hybrid project setting

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Abstract

Hybrid infrastructure projects are defined as triads of on-site/coordination/off-site project dimensions. Interaction of uncertainties in such settings result in deviations from project objectives by causing time and cost overruns, safety issues, quality deficiencies, technical problems, and lack of client satisfaction. To address these, a holistic approach in identifying and analyzing risks in hybrid (multi-dimensional) projects is proposed. Towards this aim, three research hypotheses are developed and tested using data from seven projects in Melbourne, Perth and Adelaide, Australia. Practical implications of triadic risk analysis in hybrid infrastructure projects suggest executives and managers to put more emphasis on risks associated with coordination of on-site and off-site project dimensions. This approach significantly decreases the chance of deviations from project objectives.

Keywords: Decision making; Delay; Integration; Empirical research; Performance measures; Prefabricated building elements; Project Management Body of Knowledge (PMBOK); Project management success; Risk management theory; Stakeholder communication; Workflow variance

1. Introduction

Infrastructure projects provide necessary services and facilities for the economy of a country or region to function (Van Os et al., 2015). Such projects include but are not limited to building bridges, roads, tunnels, pipelines, electrical and telecommunication networks. Off-site construction processes have been increasingly used to deliver infrastructure projects (Construction, 2011). A side-by-side progression of site-built and off-site activities in hybrid infrastructure projects provides many benefits such as schedule improvements (Dzeng and Lee, 2007), project cost savings (Arashpour et al., 2014a, 2014b), quality enhancements (Kim et al., 2014), site accident reductions (Blismas et al., 2006), and sustainability improvements (Xu et al., 2012).

However, activities in hybrid infrastructure project are often undertaken under uncertainty. Within the on-site dimension of such projects, there is uncertainty associated with weather conditions (Chan and Au, 2007), quality of assembly and installations (Gibb and Isack, 2003), and safety of heavy crane operations (Li et al., 2012). Within the off-site dimension of hybrid infrastructure projects, uncertainty is present in equipment failure rates (Ren et al., 2013), continuity of material supply (Arashpour et

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al., 2013), and precision of prefabrication (Yung and Yip, 2010). Furthermore, there is a third coordination dimension to hybrid projects that consists of transportation and communication activities with relevant associated uncertainty. Fig. 1 illustrates a simplified work breakdown structure for hybrid infrastructure projects as off-site/coordination/on-site triads.

The interaction and integration of uncertainty in the three dimensions of hybrid infrastructure projects result in the risk of deviations from project objectives (Zhao et al., 2013). Project management literature has reported many examples of time overruns (Hwang et al., 2014; Arashpour and Wakefield, 2015), cost overruns (Cooper et al., 1985; Nasirzadeh et al., 2014), safety issues (Nieto-Morote and Ruz-Vila, 2011; Wang and Yuan, 2011), and quality problems (Zeng et al., 2007) as results of underestimating the extent of risks in different project dimensions. However, there are very few examples of integrated management of interacting risks across different dimensions of hybrid projects (Acebes et al., 2014; Marle, 2015; Arashpour et al., 2016a, 2016b, 2016c).

In order to bridge this gap, the current study identifies most significant risks in three hybrid project dimensions of on-site, off-site, and coordination. It then conducts both dyadic and triadic analysis of risks in hybrid infrastructure projects. The main objective of the research is to investigate whether risks associated with off-site and on-site dimensions have similar probability of occurrence and also impact on project objectives. Furthermore, the paper seeks understanding on risk dynamics in hybrid projects as on-site/coordination/off-site triads by scrutinizing the significance of deviations from project objectives caused by risks associated with the three dimensions.

The paper consists of developing a conceptual framework and three research hypotheses based on empirical research. After testing the hypotheses, conclusions are drawn and opportunities for future research are suggested.

2. Conceptual framework

Uncertainty in projects is defined as the state of information deficiency related to knowledge of an event, its likelihood, or consequence (ISO31000, 2009) and risk is the effect of uncertainty on project objectives (PMBOK, 2013). Management of risks in contemporary projects is becoming more complex as a result of strongly interrelated risks (Zwikael and Ahn, 2011; Krane et al., 2012; Marle, 2012). The mainstream research in the project management domain proposes the use of classic project risk management (PRM) processes for risk identification, evaluation and analysis (Shen, 1997; Barki and Suzanne Rivard, 2001; Fang et al., 2012). More innovative risk management approaches aim to depart from the individual management of risks and break the propagation transitions among interrelated risks (Billio et al., 2012; Arashpour et al., 2016a, 2016b, 2016c; Bredillet and Tywoniak, 2016).

Project risk management is a systematic approach to identify, analyze, respond, and control risks with the aim of increasing the impact and likelihood of positive events, and reduce those of negative events (Raz and Michael, 2001; Ward

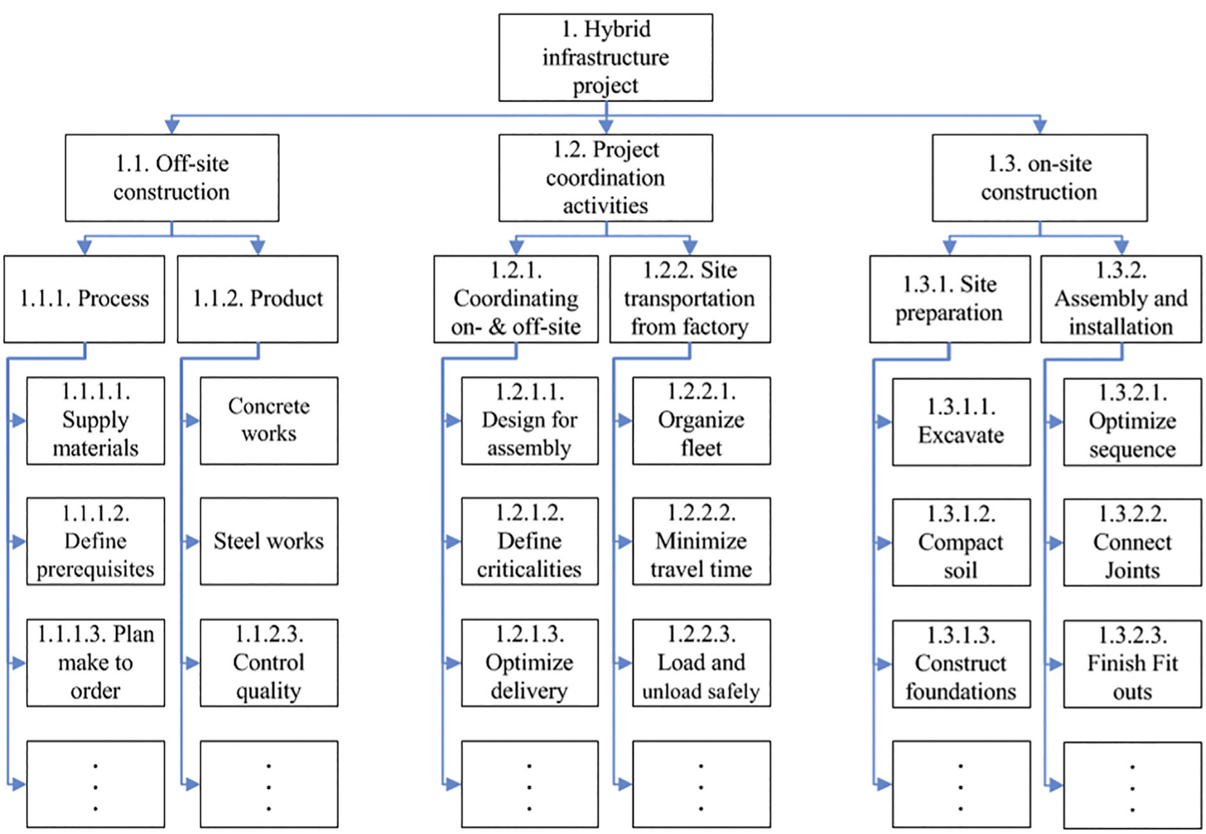


Fig. 1. Simplified subdivision of work in hybrid infrastructure projects.

and Chapman, 2003). In the risk identification process, risks that may impact project objectives are determined (Lyons and Skitmore, 2004; Arashpour et al., 2015a, 2015b). Different tools and techniques can be used for project risk identification such as documentation reviews (Marcelino-Sádaba et al., 2014), Delphi technique (Ke et al., 2010), SWOT analysis (Kwak and Smith, 2009), checklist analysis (Marle and Gidel, 2015), expert judgment (Khodakarami and Abdi, 2014), assumption analysis (Chapman, 2006), and diagramming techniques (Dikmen et al., 2007). As an example, Fig. 2 shows a cause and effect diagram developed in the current research for risk identification in hybrid infrastructure projects.

Identified project risks should be rated and prioritized for further qualitative or quantitative analysis (Khazaeni et al., 2012). Risks are rated based on their occurrence probability and impact on project objectives (Shi et al., 2014). A look-up matrix is a useful tool to define risk ratings (Hartono et al., 2014). Matrices of probability-impact are often designed based on project size and ability of project organization to effectively respond to the risk resolution level (Elkington and Smallman, 2001). Within the infrastructure project settings, considering five to seven levels of probability and impact is practical (Arashpour et al., 2014a, 2014b; Espinoza, 2014). In the developed look-up matrix (Table 1), occurrence probability ranges between 0.05 and 0.95, and impact ranges from 0.05 (very low level of impact) to 0.8 (very high level of impact).

3. Hypothesis development

Risks in hybrid infrastructure projects are triggered by existence of uncertainty in different project dimensions of on-site, off-site and coordination (see Fig. 2). As an example, unsuitable soil conditions can be a hindrance to on-site installation activities and halt the successive project activities (Hosseini et al., 2016). Another example in off-site project dimension is the issue of code compliance that often causes delays and deviations from project plans (Windapo, 2013). Previous research has shown the effectiveness of integrated risk management approaches in hybrid and complex projects (Marle et al., 2013; Fang and Marle, 2015). However, the required risk management efforts are not necessarily the same in off-site and on-site project dimensions (Arashpour et al., 2015a, 2015b). The existence of uncertainty in each project dimension and interacting effects play certain roles in this scenario and lead to the development of first hypothesis in this research,

Hypothesis 1 (H1). In a dyadic risk analysis in hybrid projects, uncertainty associated with off-site and on-site dimensions have similar impact on project objectives.

A combination of prefabrication and site-built activities is concurrently in progress in hybrid infrastructure projects. In the off-site dimension of hybrid projects, different construction elements are prefabricated in production plants using semi-automated processes (Arashpour et al., 2016a, 2016b, 2016c). On-site activities are mainly preparation for install and assembly of prefabricated elements, and include foundation construction, erecting by crane, welding, grouting, patching and caulking (Polat et al., 2006). Uncertainty presence in hybrid project dimensions results in potential risks affecting one or more project objective(s) including time, cost, scope, quality, safety and environment (Zhang, 2011; Lehtiranta, 2014). However, the occurrence probability of risks within off-site and on-site project dimensions are not necessarily the same in hybrid infrastructure projects (Schleifer, 2013). For example factors such as inclement weather conditions, human errors and accidents are mainly relevant to the on-site dimension of hybrid projects and alter the occurrence probability of risks within this dimension (Kim et al., 2016). Consequently, the second hypothesis of the paper is advanced as,

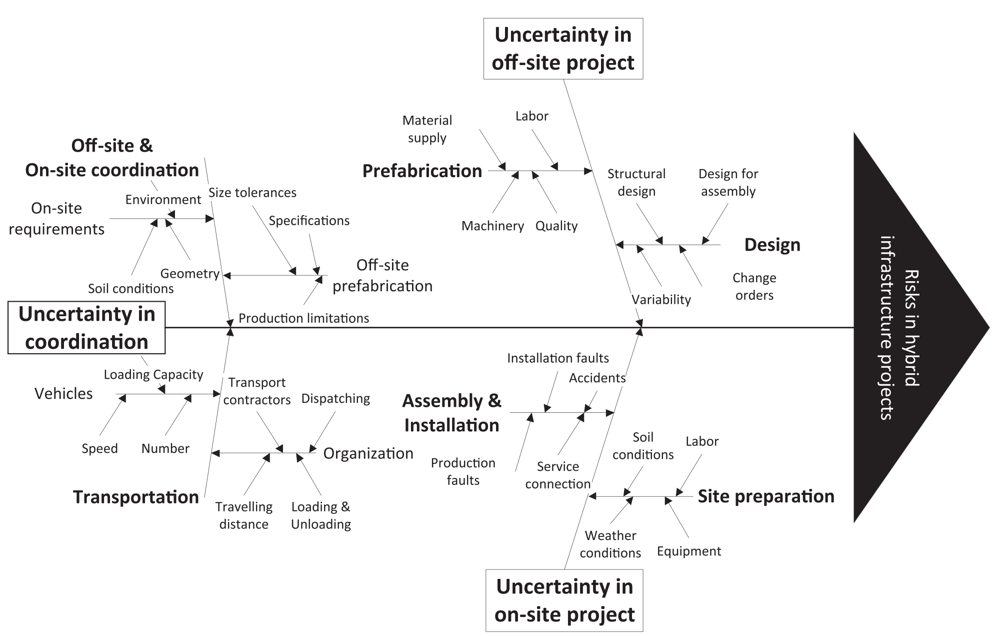


Fig. 2. Risk identification by fishbone or Ishikawa diagramming in hybrid infrastructure projects.

Table 1
Probability and impact matrix for hybrid infrastructure projects.

Probability	**0.95**	0.0475	0.095	0.19	0.38	0.57	0.665	0.76
	0.8	0.04	0.08	0.16	0.32	0.48	0.56	0.64
	0.65	0.0325	0.065	0.13	0.26	0.39	0.455	0.52
	0.5	0.025	0.05	0.1	0.2	0.3	0.35	0.4
	0.35	0.0175	0.035	0.07	0.14	0.21	0.245	0.28
	0.2	0.01	0.02	0.04	0.08	0.12	0.14	0.16
	0.05	0.0025	0.005	0.01	0.02	0.03	0.035	0.04
		0.05	**0.1**	**0.2**	**0.4**	**0.6**	**0.7**	**0.8**
		Low level of impact →					High level of impact	

Hypothesis 2 (H2). In a dyadic risk analysis in hybrid projects, risks associated with off-site and on-site dimensions have similar probability of occurrence.

Both H1 and H2 consider hybrid projects as off-site/on-site dyads to analyze the probability and impact of project risks. A more comprehensive and integrated analysis of risks can be conducted by considering hybrid infrastructure projects as triads of on-site/coordination/off-site (Arashpour et al., 2016a, 2016b, 2016c). This approach facilitates modeling and analysis of interacting uncertainties within the three project dimensions and leads to the development of the final hypothesis in this research,

Hypothesis 3 (H3). In hybrid projects as on-site/coordination/off-site triads, risks associated with the three dimensions are equally significant in causing deviations from project objectives.

4. Research method

4.1. Empirical research

This research aims to conduct an integrated risk analysis within the hybrid project settings in order to test the three developed hypotheses. Towards this aim, empirical research methodology is adopted and important variables to model risks are operationalized. Required data to run models were collected from seven hybrid infrastructure projects in Australia using a combination of project documentation reviews, cause and effect diagramming, and Delphi technique. The use of a hybrid method for data collection reduces bias in the data (Floricel et al., 2014; Arashpour and Arashpour, 2015; Davis, 2016), and prevents individual project stakeholders to have undue influence on research results (Lucko and Rojas, 2009; Taroun, 2013).

A total of 256 major risks were identified by using the combination of aforementioned methods. Delphi participants in the investigated hybrid projects included risk management team members, project managers, project team members, and risk experts from outside project teams. The identified risks by the 36 participants were categorized and recirculated to the participants for identifying the most significant risks, and assigning probability and impact. Consensus was reached in the third round and from 256 major risks, 40 were identified as most important contributors to deviations from hybrid project objectives (see Table 2).

4.2. Variable operationalization

Risk significance is calculated as the product of occurrence probability and risk impact on one or more project objective(s).

Table 2
Top 40 risks in hybrid projects as off-site/coordination/on-site triads.

Risk ID	Description	Affected part of the hybrid project
R1	Design not suitable for prefabrication	Off–site
R2	Poor quality of prefabricated products	Off–site
R3	Shortage of material supply	Off–site
R4	Difficulties with labor unions	Off–site
R5	High quality/performance expectations	Off–site
R6	General safety accidents in the factory	Off–site
R7	Demand variability for prefabrication	Off–site
R8	High inventory cost	Off–site
R9	Inefficient cost estimating for prefabrication	Off–site
R10	Change orders	Off–site
R11	Unrealistic prefabrication schedule	Off–site
R12	Design not suitable for transportation	Coordination
R13	Lack of efficient communication	Coordination
R14	Poor fleet management	Coordination
R15	Late engagement of contractors	Coordination
R16	Hidden costs for hybrid projects	Coordination
R17	Lack of compliance to requirements/standards	Coordination
R18	Volumetric limitations for transport	Coordination
R19	Excessive approval procedures for oversize loads	Coordination
R20	Damage to prefabricated elements	Coordination
R21	Unrealistic transportation schedule	Coordination
R22	General safety accidents in transportation	Coordination
R23	Excessive approval procedures–finance	Coordination
R24	Not meeting sustainability requirements	Coordination
R25	Low completion percentage in factory	Coordination
R26	Conflicting stakeholder interests	Coordination
R27	Issues around permitting and construction codes	Coordination
R28	Long distance of factory to site	Coordination
R29	Shortage of contractors' knowledge & skills	Coordination
R30	Design not suitable for assembly and installation	On–site
R31	Technical faults in installation	On–site
R32	General safety accidents on construction site	On–site
R33	Unrealistic on–site project schedule	On–site
R34	Inadequate site information	On–site
R35	Height limitations for crane lifting	On–site
R36	Inefficient cost estimating for on–site activities	On–site
R37	Disputes and contractual problems	On–site
R38	Inadequate utility infrastructure	On–site
R39	Inclement weather conditions	On–site
R40	Difficulty in site access for heavy cranes	On–site

Delphi technique results in obtaining different probability estimations and the average value for probability of occurrence ($\gamma_{(ave)}$) for any risk R_i can be calculated using Eq. (1),

$$\gamma_{(ave)} = \sum_{j=1}^{j=m} \gamma_{(e_j)}/m \tag{1}$$

where $\gamma_{(e_j)}$ is one of the m estimates of occurrence probability ($1 \leq j \leq m$).The impact of risk R_i is computed on n different project objectives ($\delta, \vartheta, \rho, \tau, \ldots, \varphi$) based on m estimates (e_1 to e_m), and the total value $\beta_{(e_j Ri)}$ for a given risks is,

$$\begin{aligned}\beta_{(e_j R_i)} = {} & \delta_{(e_1 R_i)} + \vartheta_{(e_1 R_i)} + \rho_{(e_1 R_i)} + \tau_{(e_1 R_i)} + \ldots + \varphi_{(e_1 R_i)} \\ & + \delta_{(e_2 R_i)} + \vartheta_{(e_2 R_i)} + \rho_{(e_2 R_i)} + \tau_{(e_2 R_i)} + \ldots + \varphi_{(e_2 R_i)} \\ & + \delta_{(e_j R_i)} + \vartheta_{(e_j R_i)} + \rho_{(e_j R_i)} + \tau_{(e_j R_i)} + \ldots + \varphi_{(e_j R_i)} \\ & \ldots \\ & + \delta_{(e_m R_i)} + \vartheta_{(e_m R_i)} + \rho_{(e_m R_i)} + \tau_{(e_m R_i)} + \ldots + \varphi_{(e_m R_i)}\end{aligned} \tag{2}$$

and the average risk impact can be calculated as,

$$\beta_{(ave)} = \beta_{(e_j R_i)}/(m \times n). \tag{3}$$

The risk significance index (RSI_{R_i}) determines the overall significance of a given risk (R_i) causing deviations from project plans, and can be computed using Eq. (4),

$$RSI_{R_i} = \gamma_{(ave)} \times \beta_{(ave)}. \quad (4)$$

Developed models (Eqs. (1) to (4)) are used to analyze on-site, off-site and coordination risks in hybrid infrastructure projects. Results of the analysis are presented in the following section.

5. Analysis and results

In the first analysis step, estimates of occurrence probability and risk impact on hybrid project objectives such as time, cost, scope, quality, safety and environment are aggregated. As can be seen in Table 3, within the off-site dimension of hybrid infrastructure projects, change orders (R10) have the highest significance (RSI_{R_i}). Within the coordination and on-site dimensions, most significant risks are lack of efficient communication (R13) and unrealistic project schedule (R33) respectively. Between-group comparison of risks in order to test the three developed hypotheses is undertaken in the following sections.

Table 3
Aggregated values of probability, impact and significance for the top 40 risks in hybrid projects.

Risk ID	$\gamma_{(ave)}$	$\beta_{(ave)}$	RSI_{R_i}
R1	0.20	0.60	0.12
R2	0.20	0.80	0.16
R3	0.05	0.40	0.02
R4	0.50	0.60	0.30
R5	0.35	0.40	0.14
R6	0.20	0.80	0.16
R7	0.35	0.70	0.245
R8	0.50	0.60	0.30
R9	0.50	0.70	0.35
R10	0.50	0.80	0.40
R11	0.35	0.70	0.245
R12	0.50	0.60	0.30
R13	0.65	0.80	0.52
R14	0.50	0.60	0.30
R15	0.65	0.70	0.455
R16	0.50	0.60	0.30
R17	0.65	0.80	0.52
R18	0.50	0.40	0.20
R19	0.95	0.40	0.38
R20	0.50	0.70	0.35
R21	0.50	0.60	0.30
R22	0.50	0.80	0.40
R23	0.95	0.40	0.38
R24	0.50	0.70	0.35
R25	0.65	0.70	0.455
R26	0.65	0.70	0.455
R27	0.50	0.60	0.30
R28	0.8	0.40	0.32
R29	0.65	0.60	0.39
R30	0.65	0.40	0.26
R31	0.80	0.20	0.16
R32	0.50	0.40	0.20
R33	0.95	0.40	0.38
R34	0.50	0.40	0.20
R35	0.65	0.20	0.13
R36	0.65	0.40	0.26
R37	0.50	0.10	0.05
R38	0.65	0.10	0.065
R39	0.50	0.05	0.025
R40	0.65	0.05	0.033

The first null hypothesis (H1), proposes that in hybrid projects as off-site/on-site dyads, risks associated with the two dimensions have similar impact on project objectives. In order to test H1, risk impacts in off-site are plotted against respective on-site values. As can be seen in Fig. 3, risks within the off-site group have risk impact mean of 0.645 with a standard deviation of 0.144. However, the second group (on-site) scores a risk impact mean of 0.245 with a standard deviation of 0.156. The large difference between means of impact in off-site/on-site dyad suggests that H1 cannot be supported.

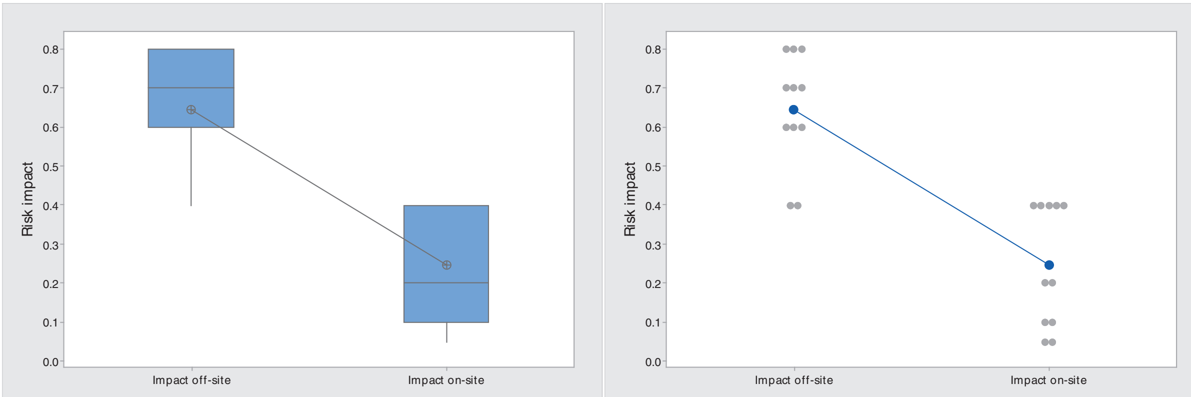
Further comparison of risk impact in the off-site/on-site dyad reveals a 95% confidence interval of [0.266, 0.534] in the mean difference. By conducting a two-sample t-test (t-value = 6.26, p-value = 0.000), the conclusion can be drawn that within hybrid project settings, off-site related risks have significantly higher impact on project objectives than on-site risks. This finding is in line with those of Li et al. (2015), confirming that risks associated with upstream activities in the long supply chain of hybrid projects can significantly impact downstream project activities and cause deviations from project objectives.

The second null hypothesis (H2) is tested by comparing the occurrence probability of risks for the off-site/on-site dyad. Risks within the off-site group have a significantly lower mean probability than on-site risks (mean = 0.336 with a standard deviation of 0.157). However, the probability in the on-site group has a mean value of 0.636 with a standard deviation of 0.142 (see Fig. 4a and b). Therefore, a non-similar risk probability is observed as opposed to H2.

Further analysis of risk probability data in the off-site/on-site dyad shows a 95% confidence interval of [−0.433,−0.167] for the probability mean difference. Rejection of H2 is also supported by t-distribution analysis (t-value = −4.71, p-value = 0.000). The results prove that in hybrid infrastructure projects, risks associated with on-site activities have higher average probability of occurrence than off-site risks. Previous research (Tennant et al., 2012; Arashpour et al., 2016a, 2016b, 2016c) suggests that risk occurrence probability in off-site is reduced because of lower involvement of human element in semi-automated processes and limited exposure to workflow variability caused by factors such as inclement weather conditions.

The third null hypothesis (H3) proposes that in hybrid infrastructure projects as off-site/coordination/on-site triads, risks are equally significant in causing deviations from project objectives. In the first step to test H3, risk significance indices (RSI_{R_i}) are tested for normality (Fig. 5a). The results of normality test prove the feasibility of using standard statistical inference to test H3. In the second step, the significance values of the three groups are plotted against one another and compared (Fig. 5b). Risks within the coordination group have a mean RSI_{R_i} of 0.371 with a standard deviation of 0.086. However, risks within off-site and on-site groups have RSI_{R_i} means of 0.222 and 0.160 with standard deviations of 0.112 and 0.113 respectively.

In the third step to test H3, analysis of variance (ANOVA) is conducted to evaluate risk significance indices in the three groups. The results (F-value = 16.60, p-value = 0.000) shows a significant difference between the mean values and therefore



a) Boxplot of risk impact in the off-site/on-site dyad **b) Individual plot of risk impact in the off-site/on-site dyad**

Fig. 3. Dyadic analysis of risk impact in hybrid infrastructure projects.

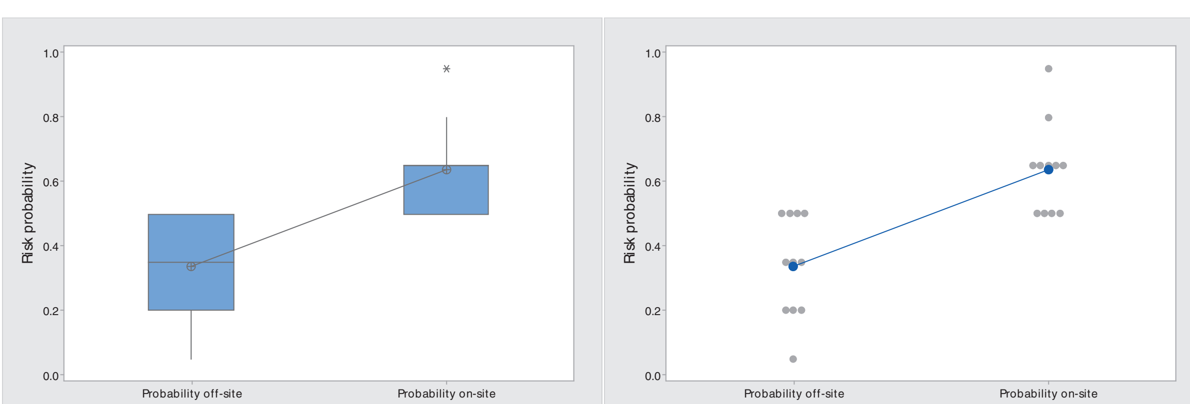
H3 cannot be supported. Furthermore, data plots in Fig. 5b support the alternative hypothesis that at least one group (coordination) in the off-site/coordination/on-site triad has a significantly higher RSI_{R_i} compared to others.

In the fourth step and to further analyze the groups' risk significance, Tukey's HSD (Honestly Significant difference) is conducted. The pairwise analysis of on-site/off-site dyad (t-value = −1.43, p-value = 0.338) does not reveal a significant difference between the two groups (see Fig. 6). However, the Tukey's results show significant differences for coordination/off-site dyad (t-value = 3.84, p-value = 0.001), and coordination/on-site dyad (t-value = 5.43, p-value = 0.000). This proves that in hybrid infrastructure projects as off-site/coordination/on-site triads, risks associated with coordinating off-site and on-site dimensions are the most significant in causing deviations from project objectives. This finding is in line with those of Bygballe et al. (2016), confirming that coordination risks in hybrid projects have the potential to impact both upstream off-site activities and downstream on-site operations and cause deviations from project objectives.

6. Conclusions

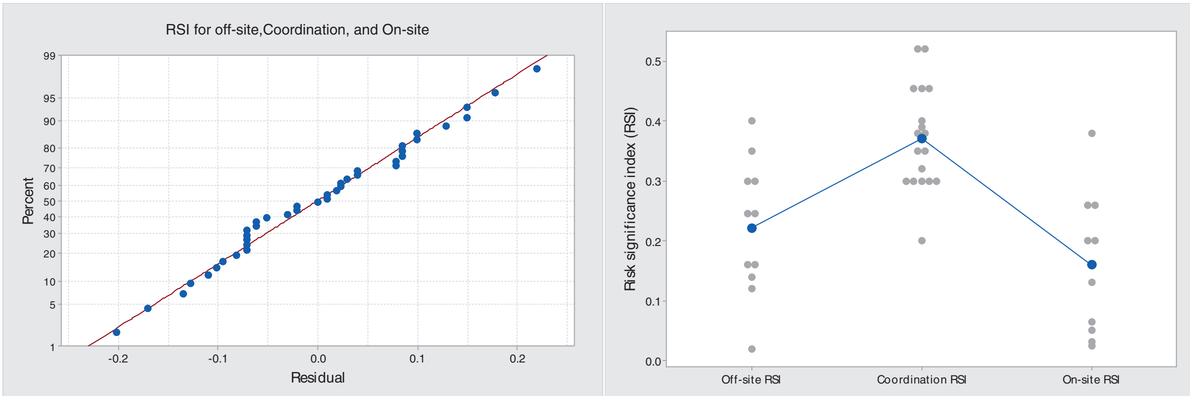
Previous research has investigated uncertainty and its effect on objectives in infrastructure projects (Chan and Au, 2007; Espinoza, 2014). With increasing use of prefabrication, such projects are transitioning to a hybrid of site-built and off-site activities with significant coordination efforts (Li and Taylor, 2014). Therefore, an integrated risk management approach is required to model and analyze uncertainty in hybrid projects. Towards this aim, the current research developed and tested three hypotheses on dynamics of risk analysis in hybrid project settings. The findings show that risks associated with coordination of on-site and off-site project dimensions are believed to be the most significant contributors to deviations from project objectives. The findings are applicable and generalizable to many project settings with division of work and labor where substantial coordination/communication is required.

This research contributes to the literature of project risk management by proposing a holistic risk analysis approach in project settings. Developed models and findings are of practical



a) Boxplot of risk probability in the off-site/on-site dyad **b) Individual plot of probability in the off-site/on-site dyad**

Fig. 4. Dyadic analysis of risk probability in hybrid infrastructure projects.



a) Normal probability plot in the hybrid project triad **b) Individual plot of significancein the hybrid project triad**

Fig. 5. Triadic analysis of risk significance in hybrid infrastructure projects.

use to project managers and senior executives by facilitating the identification and analysis of risks in different dimensions of high-risk projects.

Finally, limitations of this research should be noted. There was limited access to the risk-related data in hybrid infrastructure projects because of stakeholder reluctance to share company/project proprietary data. Future research should use larger sample sizes of international projects and rigorously examine the generalizability of findings to other multi-dimensional (hybrid) project settings. More objective testing of the developed hypotheses requires an analysis of project activities on the ground and related risks.

Conflict of interest

There is no conflict of interest.

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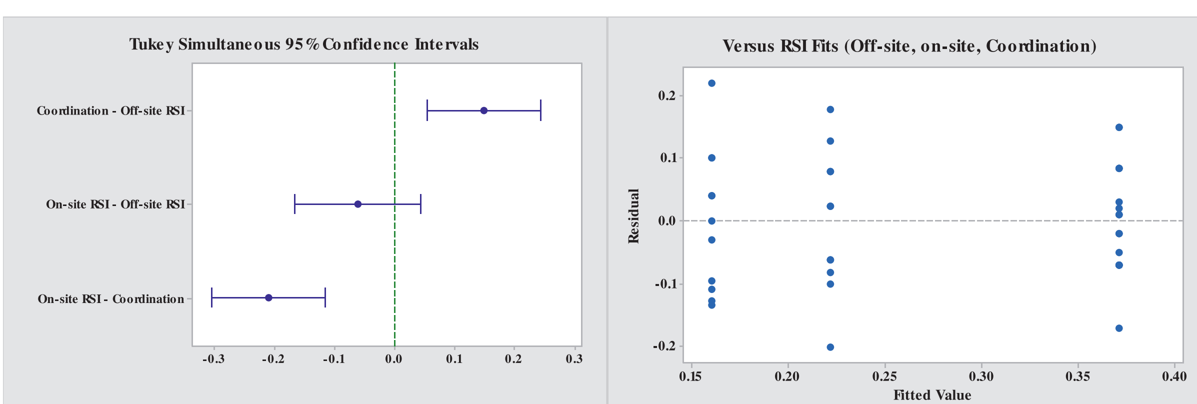
Appendix A. Notation and symbols

$\gamma_{(ave)}$	Risk probability of occurrence (average value)
$\beta_{(ave)}$	Risk impact on objectives (average value)
RSI_{R_i}	Risk significance index for ith risk
$\gamma_{(e_jRi)}$	jth estimate of ith risk probability of occurrence
$\delta_{(e_jRi)}$	jth estimate of ith risk impact on time objective
$\vartheta_{(e_jRi)}$	jth estimate of ith risk impact on cost objective
$\rho_{(e_jRi)}$	jth estimate of ith scope impact on time objective
$\tau_{(e_jRi)}$	jth estimate of ith risk impact on quality objective
$\varphi_{(e_jRi)}$	jth estimate of ith risk impact on environmental objective

References

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.



a) Tukey's HSD - Difference of means in the hybrid triad **b) Versus fit of risk significance indices in the triad**

Fig. 6. Multiple comparisons of means for risk significance in hybrid infrastructure projects.

Arashpour, M., Arashpour, M., 2015. Analysis of workflow variability and its impacts on productivity and performance in construction of multistory buildings. J. Manag. Eng. 31 (6), 04015006.

Arashpour, M., Wakefield, R., 2015. Developing an uncertainty analysis model for off-site building production. 8th International Structural Engineering and Construction Conference: Implementing Innovative Ideas in Structural Engineering and Project Management, ISEC 2015. ISEC Press.

Arashpour, M., Wakefield, R., Blismas, N., Lee, E.W.M., 2013. A new approach for modelling variability in residential construction projects. Australas. J. Constr. 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, 72–80.

Arashpour, M., Wakefield, R., Abbasi, B., Lee, E.W.M., Minas, J., 2016a. Off-site construction optimization: sequencing multiple job classes with time constraints. Autom. Constr. 71, 262–270.

Arashpour, M., Wakefield, R., Blismas, N., Abbasi, B., 2016b. 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.

Arashpour, M., Wakefield, R., Lee, E.W.M., Chan, R., Hosseini, M.R., 2016c. Analysis of interacting uncertainties in on-site and off-site activities: implications for hybrid construction. Int. J. Proj. Manag. 34 (7), 1393–1402.

Barki, H., Suzanne Rivard, J.T., 2001. An integrative contingency model of software project risk management. J. Manag. Inf. Syst. 17 (4), 37–69.

Billio, M., Getmansky, M., Lo, A.W., Pelizzon, L., 2012. Econometric measures of connectedness and systemic risk in the finance and insurance sectors. J. Financ. Econ. 104 (3), 535–559.

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

Bredillet, C.N., Tywoniak, S., 2016. Genesis of the special issue. Int. J. Proj. Manag. 34 (7), 1322–1327.

Bygballe, L.E., Swärd, A.R., Vaagaasar, A.L., 2016. Coordinating in construction projects and the emergence of synchronized readiness. Int. J. Proj. Manag. 34 (8), 1479–1492.

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.

Chapman, C., 2006. Key points of contention in framing assumptions for risk and uncertainty management. Int. J. Proj. Manag. 24 (4), 303–313.

Construction, M.H., 2011. Prefabrication and modularization: increasing productivity in the construction industry. Smart Market Report.

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

Davis, K., 2016. A method to measure success dimensions relating to individual stakeholder groups. Int. J. Proj. Manag. 34 (3), 480–493.

Dikmen, I., Birgonul, M.T., Han, S., 2007. Using fuzzy risk assessment to rate cost overrun risk in international construction projects. Int. J. Proj. Manag. 25 (5), 494–505.

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.

Elkington, P., Smallman, C., 2001. Managing project risks: a case study from the utilities sector. Int. J. Proj. Manag. 20 (1), 49–57.

Espinoza, R.D., 2014. Separating project risk from the time value of money: a step toward integration of risk management and valuation of infrastructure investments. Int. J. Proj. Manag. 32 (6), 1056–1072.

Fang, C., Marle, F., 2015. A framework for the modeling and management of project risks and risk interactions. Handbook on Project Management and Scheduling. vol. 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.

Floricel, S., Bonneau, C., Aubry, M., Sergi, V., 2014. Extending project management research: insights from social theories. Int. J. Proj. Manag. 32 (7), 1091–1107.

Gibb, A.G.F., Isack, F., 2003. Re-engineering through pre-assembly: client expectations and drivers. Build. Res. Inf. 31 (2), 146–160.

Hartono, B., Sulistyo, S.R., Praftiwi, P.P., Hasmoro, D., 2014. Project risk: theoretical concepts and stakeholders' perspectives. Int. J. Proj. Manag. 32 (3), 400–411.

Hosseini, M.R., Chileshe, N., Jepson, J., Arashpour, M., 2016. Critical success factors for implementing risk management systems in developing countries. Constr. Econ. Build. 16 (1), 18–32.

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.

Ke, Y., Wang, S., Chan, A.P.C., Lam, P.T.I., 2010. Preferred risk allocation in China's public-private partnership (PPP) projects. Int. J. Proj. Manag. 28 (5), 482–492.

Khazaeni, G., Khanzadi, M., Afshar, A., 2012. Fuzzy adaptive decision making model for selection balanced risk allocation. Int. J. Proj. Manag. 30 (4), 511–522.

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, M.K., Sohn, H., Chang, C.C., 2014. Automated dimensional quality assessment of precast concrete panels using terrestrial laser scanning. Autom. Constr. 45, 163–177.

Kim, Y.W., Han, S.H., Yi, J.S., Chang, S.W., 2016. Supply chain cost model for prefabricated building material based on time-driven activity-based costing. Can. J. Civ. Eng. 43 (4), 287–293.

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.

Kwak, Y.H., Smith, B.M., 2009. Managing risks in mega defense acquisition projects: performance, policy, and opportunities. Int. J. Proj. Manag. 27 (8), 812–820.

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

Li, Y., Taylor, T.R.B., 2014. Modeling the impact of design rework on transportation infrastructure construction project performance. J. Constr. Eng. Manag. 140 (9).

Li, H., Chan, G., Skitmore, M., 2012. Multiuser virtual safety training system for tower crane dismantlement. J. Comput. Civ. Eng. 26 (5), 638–647.

Li, H., Lu, M., Chan, G., Skitmore, M., 2015. Proactive training system for safe and efficient precast installation. Autom. Constr. 49 (PA), 163–174.

Lucko, G., Rojas, E., 2009. Research validation: challenges and opportunities in the construction domain. J. Constr. Eng. Manag. 136 (1), 127–135.

Lyons, T., Skitmore, M., 2004. Project risk management in the Queensland engineering construction industry: a survey. Int. J. Proj. Manag. 22 (1), 51–61.

Marcelino-Sádaba, S., Pérez-Ezcurdia, A., Echeverría Lazcano, A.M., Villanueva, P., 2014. Project risk management methodology for small firms. Int. J. Proj. Manag. 32 (2), 327–340.

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.

Marle, F., Gidel, T., 2015. Assisting project risk management method selection. Int. J. Proj. Organ. Manag. 6 (3), 254–282.

Marle, F., Vidal, L.A., Bocquet, J.C., 2013. Interactions-based risk clustering methodologies and algorithms for complex project management. Int. J. Prod. Econ. 142 (2), 225–234.

Nasirzadeh, F., Khanzadi, M., Rezaie, M., 2014. Dynamic modeling of the quantitative risk allocation in construction projects. Int. J. Proj. Manag. 32 (3), 442–451.

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

PMBOK, 2013. Guide to the Project Management Body of Knowledge. fifth ed. Project Management Institute, Pennsylvania USA.

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

Raz, T., Michael, E., 2001. Use and benefits of tools for project risk management. Int. J. Proj. Manag. 19 (1), 9–17.

Ren, Z., Shen, G.Q., Xue, X.L., 2013. Failure caused by inappropriate construction methods: an expensive lesson. J. Manag. Eng. 29 (1), 25–34.

Schleifer, T.C., 2013. The new rules of risk include an increased threat of contractor default. ENR (Engineering News-Record). 271(11).

Shen, L., 1997. Project risk management in Hong Kong. Int. J. Proj. Manag. 15 (2), 101–105.

Shi, Q., Zhou, Y., Xiao, C., Chen, R., Zuo, J., 2014. Delivery risk analysis within the context of program management using fuzzy logic and DEA: a China case study. Int. J. Proj. Manag. 32 (2), 341–349.

Taroun, A., 2013. Towards a better modelling and assessment of construction risk: insights from a literature review. Int. J. Proj. Manag. (0).

Tennant, S., McCarney, M., Tong, M.K.L., 2012. Re-engineering the construction supply chain: transferring on-site activity, offsite. 28th Annual Conference of the Association of Researchers in Construction Management, ARCOM 2012. Association of Researchers in Construction Management.

Van Os, A., Van Berkel, F., De Gilder, D., Van Dyck, C., Groenewegen, P., 2015. Project risk as identity threat: explaining the development and consequences of risk discourse in an infrastructure project. Int. J. Proj. Manag. 33 (4), 877–888.

Wang, J., Yuan, H., 2011. Factors affecting contractors' risk attitudes in construction projects: case study from China. Int. J. Proj. Manag. 29 (2), 209–219.

Ward, S., Chapman, C., 2003. Transforming project risk management into project uncertainty management. Int. J. Proj. Manag. 21 (2), 97–105.

Windapo, A., 2013. Relationship between degree of risk, cost and level of compliance to occupational health and safety regulations in construction. Australas. J. Constr. Econ. Build. 13 (2), 67–82.

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.

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, H., 2011. Two schools of risk analysis: a review of past research on project risk. Proj. Manag. J. 42 (4), 5–18.

Zhao, X., Hwang, B.-G., Yu, G.S., 2013. Identifying the critical risks in underground rail international construction joint ventures: case study of Singapore. Int. J. Proj. Manag. 31 (4), 554–566.

Zwikael, O., Ahn, M., 2011. The effectiveness of risk management: an analysis of project risk planning across industries and countries. Risk Anal. 31 (1), 25–37.