Fuzzy Integral–Based Risk-Assessment Approach for Public–Private Partnership Infrastructure Projects

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Abstract: Adequate assessment of risk is essential to assist the stakeholders in planning for efficient risk allocation and mitigation and to ensure success in business and projects. However, it is problematic due to the difficulty in quantification of certain risks, existence of interactions, and multiattribute structure of the project risk assessment task. This paper reports research in which relevant risks were identified for power and transport infrastructure public-private partnership (PPP) projects, which are globally the most active infrastructure sectors for private investment. It further proposes, demonstrates, and validates a novel multiattribute risk assessment model that supports both sectoral and project risk analysis to assist stakeholders in risk management decision making. A 45-factor risk register, established based on literature review and PPP experts' interviews, was administered to solicit industry-wide perceptions for risk assessment. Application of fuzzy set theory to risk analysis revealed 22 critical risk factors (CRFs) that were categorized into seven critical risk groups (CRGs) of correlated factors using factor analysis. Risk factors that achieved a linguistic assessment of high impact reflect issues related to institutional capacity and the local economy. Further analysis based on fuzzy measure and nonadditive fuzzy integral combined with arithmetic mean helped to obtain an overall risk index (ORI) which indicated a moderate risk outlook for both power and transport infrastructure sectors. Whereas public sector maturity was assessed as a high impact CRG in the power sector, project planning and implementation, project finance, and project revenue were additionally rated as high impact CRGs in the transport infrastructure sector. Demonstration of the developed methodology for a build-operate-transfer (BOT) motorway case study project showed that the private sector stakeholders viewed the project at high risk with all the CRGs evaluated as high impact except the political stability CRG, which was assessed as moderately risky. Test results show that the methodology performed satisfactorily in approximating experts holistic project risk assessments. The developed framework can be used to assess a country's condition or overall project risk at the initial project stage with little input of time and resources, thus facilitating an efficient and robust risk assessment. Application of fuzzy measure based nonadditive fuzzy integral combined with arithmetic mean for sectoral and project risk assessment, and comparison of sectoral risk analysis from a developing country perspective are some of the key features of this study. **DOI: 10.1061/(ASCE)CO.1943-7862.0001573.**

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Introduction

Delivering infrastructure projects through private sector participation via public-private partnerships (PPPs) is arguably an efficient means of fulfilling public infrastructure needs. This approach allows for increased integration of design, finance, construction, operation, and maintenance into a single contract (Yescombe 2007), and provides a medium to tap into private sector expertise (Marques and Berg 2011), whereas the government can focus on policy, planning, and regulation by delegating project operations (World Bank 2016). In addition, this approach to project delivery also provides for bringing in private capital for public service delivery thus enabling the governments to cope with ever tightening budget and public borrowing constraints (Allen & Overy 2010). Both the aspects of efficiency and funding may become even more critical when considering developing countries, which experience large skill gaps, poor governance, and budget constraints. Pakistan, a developing country, is facing an acute shortage of infrastructure in virtually all sectors, and ranks 116 out of 138 countries in infrastructure (Schwab 2016). PPPs have been recognized as a partial solution to fulfilling public infrastructure needs in the short-term (Mazher et al. 2017). The country has witnessed significant private-sector investment in the power sector (power generation projects) followed by a relatively new founded interest in procurement of transport infrastructure projects through PPPs with some road/highway projects recently becoming operational.

Besides offering the prospects to fulfill infrastructure needs, PPPs boast a relatively higher risk profile for all the stakeholders, which can result in poor outcomes/failures, if not identified and managed properly. PPP projects in Pakistan face multiple risks (Economist Intelligence Unit 2015; Fraser 2005; Sachs et al. 2007; Soomro and Zhang 2011); however, a systematic investigation of such risks is yet to be conducted (Mazher et al. 2017). Several contextual factors influence risks and their management which include: country, sector, and project characteristics;

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differences in capabilities of the project participants; and working practices and strategies (Ameyaw and Chan 2013; Carbonara et al. 2015; Ibrahim et al. 2006; Ng and Loosemore 2007). Hence, there is a need to explore risks in the relatively young history of PPP based procurement of infrastructure projects in Pakistan. Research on risks and their management in power and transport infrastructure sectors deserves more attention as they account for the largest share of global private investment in public infrastructure in low- and middle-income countries (World Bank 2018). This may also be significant because many PPP projects in developing countries are financed internationally; hence, the outcomes will be relevant to both local and international practitioners and researchers. Furthermore, the need for an objective, reliable, and practical risk assessment model has been stressed in the existing research on PPPs (Jin and Doloi 2008; Li and Zou 2011). In addition to assessing risks individually, it is important to assess the overall risk level of various risk groups and the project. This may enable stakeholders to better assess risks and their impacts, plan and develop mitigation measures, and compare projects in terms of their overall riskiness to either avoid very risky projects or to bring to focus those projects that require more attention (Ameyaw and Chan 2015b; Zayed et al. 2008; Zayed and Chang 2002). Evaluating project risk level may be especially useful for firms considering penetration into foreign PPP markets to promote various projects, where unfamiliarity with the geography, supply chain, local codes, and business practices increase uncertainty (Rebeiz 2012). A number of models exist in the literature to assess project risks (Ameyaw et al. 2017; Ameyaw and Chan 2015b; Wang and Elhag 2007; Xu et al. 2010; Zayed et al. 2008). In traditional multicriteria evaluations, criteria are assumed to be independent; however, the condition of criteria independence is usually not applicable in real world problems (Liou and Tzeng 2007).

Keeping in view the state of existing research, the paper sets out to explore and achieve multiple tasks. These include: (1) identification of actual risks being encountered on PPP infrastructure projects, (2) evaluation of stakeholders' perceptions with respect to criticality of identified risks, and (3) development of a model to assess the risk level of various CRGs, overall project riskiness, and the overall risk level of PPP projects in the country, while accounting for complex interactions between risks. Besides the introduction in section one, section two presents literature review on existing research in risk identification and assessment of PPPs along with background on fuzzy measure and fuzzy integral application in research. Section three focuses on research methodology and essential concepts related to fuzzy set theory, fuzzy measures, and fuzzy integrals. Section four sheds light on data analysis results, whereas section five presents a stepwise process on development and application of the Choquet fuzzy integral model for sectoral and project risk assessment. Discussion on results is covered in section six which is followed by model validation in section seven. The paper ends with conclusions and recommendations.

Previous Research on Risk Management in PPPs

Based on a review of literature, Loosemore and Cheung (2015) advocated that all construction projects involve significant risks; however, characteristic long duration, scope, and complexity of PPPs add to the overall risk portfolio which includes regulatory, political, financial, sponsor, market, interface, technical, operational, and industrial relation risks. Both the public and private sectors need to develop an understanding of these life-cycle risks to ensure long-term success (Ibrahim et al. 2006). Akintoye et al. (1998) surveyed the perceptions of clients, contractors, and lenders on risks associated with private finance initiative projects in the United Kingdom and identified design risk, construction cost risk, performance risk, risk of delay, and cost overrun risk as the top five most significant risk factors. They further contended that each group of respondents tended to rank those risk factors as significant which were paramount to their business objectives. A questionnaire survey to determine public and private sector risk perceptions in Nigeria revealed unstable government, inadequate experience in PPP, and availability of finance as the three most important risk factors (Ibrahim et al. 2006). Roumboutsos and Anagnostopoulos (2008) studied risk perceptions among PPP stakeholders in Greece where professionals from construction, public sector, and financing institutions rated different mixes of risk factors as the most significant among the top five. The factors include: delays in project approvals and permits, poor public decision-making process, construction cost overrun, change in tax regulation, operational revenues below expectation, public opposition to the project, operation cost overrun, poor financial market, late design changes, inadequate experience in PPP, change in construction legislation, and archeological findings. Chan et al. (2011), while studying risks in Chinese PPP projects, determined government intervention, government corruption, poor public decision-making processes, financing risk, and imperfect law and supervision systems as the top five critical risks. Hwang et al. (2013) examined the critical risks factors in PPP projects in Singapore and obtained lack of support from government, availability of finance, construction time delay, inadequate experience in PPP, and unstable government as the top five ranked risk factors. Osei-Kyei and Chan (2017) studied and compared risk factors in PPP projects between Ghana and Hong Kong, and found that country risk factors were ranked higher in Ghana (corruption, inflation rate fluctuation, exchange rate fluctuation, delay in project completion, and interest rate fluctuation rated as the top five). However, project-specific risks were ranked higher in Hong Kong (delay in land acquisition, operational cost overruns, construction cost overruns, delay in project completion, and political interference rated as the top five). Thomas et al. (2003) explored the perceptions of key stakeholders towards critical risks in the roads sector under build-operate-transfer (BOT) arrangement in India. Traffic revenue risk, delay in land acquisition, demand risk, delay in financial closure, completion risk, cost overrun risk, debt servicing risk, and direct political risks were found to be very critical, in descending order. Wibowo and Mohamed (2010) investigated the perceptions of both regulators and operators with reference to project risk criticality and allocation in Indonesia's water-supply projects. The five most critical risks determined by the regulators include: nonavailability of raw water, entry of new competitors, construction cost escalation, equipment defect-caused interruption, and operation and maintenance cost escalation. Whereas tariff setting uncertainty, breach of contract agreement, nonavailability of raw water, construction time overrun, and construction cost escalation were rated as the five most critical risk factors by the operators. The top five most significant risk factors influencing implementation of PPP water supply infrastructure projects in Ghana were reported as foreign exchange rate, corruption, water theft, nonpayment of bills, and political interference (Ameyaw and Chan 2015a). It is apparent from the review of the selected studies above that the critical risks vary depending upon country and sector characteristics. Furthermore, there is little research available that compares risks and their significance across infrastructure sectors (Cheung and Chan 2011) with only a few works providing insights on some critical risks in power sector PPP projects (Rebeiz 2012; Schaufelberger and Wipadapisut 2003; Wang et al. 2000a, b; Xu et al. 2015).

According to Chinyio and Fergusson (2003), qualitative, semi-quantitative, and quantitative methods are employed in risk analysis for PPP projects; however, the use of each method is driven by the availability of information on risk attributes such as probability and severity of different risks. Due to the unique nature of such projects and the fact that the history of such schemes is still young (applies more to countries that have recently adopted PPP schemes to deliver projects), the data required for a quantitative assessment may not be applicable for analysis or are unavailable altogether (Dey and Ogunlana 2004). Another limitation stems from the peculiar nature of many risks in PPP projects that restricts opportunities for adequate mathematical modeling, thus allowing only qualitative analysis of risks such as environmental risks, political and nonpolitical risks, and delay in land acquisition. (Iyer and Sagheer 2010). Hence, risk analysis is a subject that is shrouded in vagueness and uncertainty (Carr and Tah 2001). The need for subjective assessment is indispensable for risk assessment of PPP projects (Dey and Ogunlana 2004). A number of methodologies and models already exist that employ qualitative data (derived from subjective judgments of knowledgeable experts) and utilize tools such as the analytical hierarchy process/analytical network process (AHP/ANP), multiattribute utility theory, and concepts from fuzzy set theory (FST) (Ameyaw et al. 2017; Ameyaw and Chan 2015b; Ebrahimnejad et al. 2010; Li and Zou 2011; Li and Wang 2016; Liu et al. 2013; Nieto-Morote and Ruz-Vila 2011; Valipour et al. 2015; Wang and Elhag 2007; Xu et al. 2010; Zayed and Chang 2002; Zegordi et al. 2012). Existing models either only rank several identified risk factors or provide a composite risk index frequently based on arithmetic mean or weighted arithmetic mean aggregation operator. The decision maker may not always have an additive measure to evaluate fuzzy objects, and the criteria employed to evaluate an object may not always be independent of each other. Hence, assumptions of additivity and independency may not hold true, thus invalidating the applicability of a linear model (Onisawa et al. 1986). In this paper, the nonadditive fuzzy integral has been employed for development of a multiattribute project risk assessment model, because it has the ability to cater to certain kinds of criteria (risks) interaction ranging from redundancy to synergy (Grabisch 1996). Decision-making models and frameworks that employ fuzzy measures and fuzzy integrals have been used previously for solving multicriteria problems (Afshari et al. 2013; Chen and Cheng 2009; Chiou et al. 2005; Dursun et al. 2011; Feng et al. 2010; Laishram and Kalidindi 2009; Liou and Tzeng 2007; Onisawa et al. 1986; Tan et al. 2011; Yang et al. 2008). In these works, methods to determine the fuzzy measure and the specific aggregation operator used may vary depending upon the specific focus and preferences of researchers.

Research Methods

Identification of Risk Factors

Risk factors were identified using a two-step approach where a comprehensive literature review of existing risk research (Akintoye et al. 1998; Ameyaw and Chan 2016; Bing et al. 2005; Chan et al. 2011; Chou and Pramudawardhani 2015; Ibrahim et al. 2006; Jin and Zhang 2011; Ng and Loosemore 2007; Özdoganm and Talat Birgönül 2000; Roumboutsos and Anagnostopoulos 2008; Shen et al. 2006; Thomas et al. 2003; Wibowo and Mohamed 2010; Xenidis and Angelides 2005) and other materials including industrial/government PPP guidelines/reports (Government of the Netherlands 2002; Partnership Victoria 2001; Phillips 2008), was supplemented with semistructured interviews from the local industry to ensure a comprehensive and representative risk register for risk assessment and model development. Semistructured interviews were conducted with experienced experts, in public and private sectors, from both the power and transport infrastructure sectors, to solicit relevant risk factors, as reported by Mazher et al. (2017). Based on the inputs of interviewed experts, two additional risk factors were identified, namely the *development risk* and *lack of skilled experts*. A unified risk register was created that contained 45 risk factors, which have been shown in Table 3, in tandem with the analytical results to conserve space.

Questionnaire Survey

Questionnaires based data collection is a popular methodology in PPP research (Zhang et al. 2016). It enables respondents to respond at their convenience and also allows for collection of a comparatively large number of responses, relatively quickly and cheaply (Mangione 1995), among other benefits. Before conducting the actual survey, the finalized questionnaire was piloted with five experts from the semistructured interview panel, which ensured a comprehensive and appropriate research instrument. The questionnaire had three sections with section one targeted at collecting background information on the respondent and parent organization, whereas, section two solicited perceptions of experts on probability and severity of identified risks, based on their experiences. The third section concerned another aspect of the broader research agenda, which has not been reported in this paper. Details of the scale employed for risk assessment are provided in the next section. Due to a lack of a centralized database of PPP experts in Pakistan, purposive sampling and semisnowballing approaches were adopted to identify and solicit input from experts that possess working experience on at least one PPP project with knowledge of risk management in the context of PPPs (Ameyaw and Chan 2015b). The criteria facilitated in ensuring that quality responses are received by allowing for careful selection of industry experts. Experts from all stakeholder groups were contacted to participate in this research including PPP units (federal/provincial), public authorities, lending institutions, investors, consultants, and project sponsors/companies.

Factor Analysis

Factor analysis (FA) is a dimension-reduction technique of multivariate statistics (Chiou et al. 2005), that reduces many interrelated variables to a small number of groups (Brown 2015). FA was employed to obtain the independent common factors (CRGs) based on interrelated subfactors (component risks). Fuzzy measure and fuzzy integral analyses were performed to obtain an aggregate assessment of risk attributes (probability and severity) within each common factor. The appropriateness of applying FA was determined by evaluating various indices such as Bartlett's test of sphericity and the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy (MSA) (Chan et al. 2010). The rotated component matrix was calculated using the Varimax rotation method.

Fuzzy Set Theory and Its Application in Multiple Criteria Decision Making

Fuzzy set theory (FST) was introduced by Zadeh (1965). It provides a useful means to deal with real-world systems that are ill defined and complex due to the lack of precise and complete information. A fuzzy set can be mathematically expressed by a membership function, which assigns a grade of membership to define the extent of association of each element in the universe of discourse to the concept represented by a fuzzy set. These membership grades are represented using real numbers that range between a closed interval of zero to one, where zero represents no membership and one represents full membership in the fuzzy set. It employs linguistic variables and terms to model the characteristic vagueness in the human cognitive process (Singh and Tiong 2005). Unlike a numerical variable, a linguistic variable's values are words or sentences in natural or artificial language (Zadeh 1975), such as the terms *Very low probability* or *Extremely important* that may be used to assess linguistic variables and vaguely express the degree of probability or importance of an event, respectively. In this research, a seven-term set (or linguistic values) and their fuzzy numbers are employed, in agreement with the pilot study experts, to enable linguistic assessment of risks' probability and severity. The term set includes *Extremely low*, *Very Low*, *Low*, *Moderate*, *High*, *Very High*, and *Extremely High*. The membership function of each linguistic term is characterized by triangular fuzzy numbers (TFN), which are defined by three parameters (left point, middle point, and the right point), that cover the range over which the function is defined (Table 1). Membership functions with triangular shape are the most common among the various shapes that are used to describe membership functions (Tah and Carr 2000; Xu et al. 2010). Also, TFN representations of subjective opinions are easy to use and intuitive (Chou and Chang 2008).

Table 1. Linguistic terms and the associated TFNs

Linguistic terms	Fuzzy number
EL (extremely low)	(0.000, 0.000, 0.150)
VL (very low)	(0.000, 0.150, 0.300)
L (low)	(0.150, 0.300, 0.500)
M (moderate)	(0.300, 0.500, 0.700)
H (high)	(0.500, 0.700, 0.850)
VH (very high)	(0.700, 0.850, 1.000)
EH (extremely high)	(0.850, 1.000, 1.000)

A TFN $\tilde{R}$ can be defined mathematically by its membership function $u_{\tilde{R}}(x)$ (Hsieh et al. 2004; van Laarhoven and Pedrycz 1983) as follows:

$$u_{\tilde{R}}(x) = \begin{cases} (x-L)/(M-L), & L \leq x \leq M, \\ (U-x)/(U-M), & M \leq x \leq U, \\ 0, & Otherwise, \end{cases}$$

Here, L, M, and U represent the lower, modal, and upper values, respectively, of the TFN $\tilde{R}$. The TFN is denoted as $\tilde{R} = (L, M, U)$. Basic arithmetic operations on two TFNs, $\tilde{A}$ (L_1, M_1, U_1) and $\tilde{B}$ (L_2, M_2, U_2), are given below (Chen and Hwang 1993):

$$\text{Addition:}\tilde{A} \oplus \tilde{B} = (L_1, M_1, U_1) \oplus (L_2, M_2, U_2) = (L_1 + L_2, M_1 + M_2, U_1 + U_2)$$

$$\text{Subtraction:}\tilde{A} \ominus \tilde{B} = (L_1, M_1, U_1) \ominus (L_2, M_2, U_2) = (L_1 - U_2, M_1 - M_2, U_1 - L_2)$$

$$\text{Multiplication:}\tilde{A} \otimes \tilde{B} = (L_1, M_1, U_1) \otimes (L_2, M_2, U_2) = (L_1 L_2, M_1 M_2, U_1 U_2) \quad \text{for } L_i > 0, M_i > 0, U_i > 0$$

$$\text{Division:}\tilde{A} \oslash \tilde{B} = (L_1, M_1, U_1) \oslash (L_2, M_2, U_2) = (L_1/U_2, M_1/M_2, U_1/L_2) \quad \text{for } L_i > 0, M_i > 0, U_i > 0$$

According to Ray (2015), the fuzzy membership function for the square root of a TFN can be derived using α-cut method. For any TFN $\tilde{R}$, the square root can be obtained as

$$\text{Square-root of } \tilde{R}\text{:}\sqrt{\tilde{R}} = (\sqrt{L}, \sqrt{M}, \sqrt{U})$$

Bellman and Zadeh (1970) were the first to explore the decision-making problem under a fuzzy environment, and this initiated the work in fuzzy multiple criteria decision making (FMCDM) to solve multiple criteria problems in the selection of alternatives. A fuzzy decision-making framework generally consists of several steps including specification of the type of fuzzy numbers and membership functions, scale of preference, fuzzy values assignment to attributes, fuzzy aggregation, defuzzification, analysis of overall importance of individual decision criteria, and ranking of alternatives (Singh and Tiong 2005). For aggregation of fuzzy numbers across multiple experts' inputs, this study uses the notion of average value (Buckley 1985). For a given alternative, if $\tilde{R}_i^k$ represents the fuzzy assessment of a criterion i by expert k then the evaluation will be given by $\tilde{R}_i^k = (L, M, U)$. The fuzzy average of assessments by all the experts will be given by

$$\tilde{R}_i = \left(\frac{1}{q}\right) \otimes (\tilde{R}_i^1 \oplus \tilde{R}_i^2 \oplus \ldots \oplus \tilde{R}_i^q) \tag{1}$$

where $\tilde{R}_i$ = average fuzzy number encapsulating the judgment of all the experts. Once the fuzzy aggregates are obtained, defuzzification to a crisp value is necessary for further processing. There are multiple methods available to perform this function; however, the most commonly used method is the centroid defuzzification, center of gravity, or center of area defuzzification. As employed by Wang and Elhag (2007) and Zhao et al. (2013), for a TFN $\tilde{R}$, the centroid defuzzification (R') is given by

$$R' = \frac{\tilde{R}}{3} = \frac{L + M + U}{3} \tag{2}$$

Fuzzy Measures and Fuzzy Integrals

To perform aggregation in a fuzzy-based decision making problem, fuzzy integrals can be employed. The term fuzzy integral is a general term for integrals based on a fuzzy measure (Grabisch et al. 2000). A Choquet fuzzy integral is one of the many families of fuzzy integrals based on a fuzzy measure that provides an alternate methodology for information aggregation (Chiang 1999).

Let $X = \{x_1, x_2, x_3, \ldots x_m\}$ be a finite set (criteria in a MCDM problem) and $P(X)$ be a power set of X. A fuzzy measure g over a set X is a function g:$P(X) \rightarrow [0, 1]$ that satisfies the following conditions (Chiang 1999; Sugeno 1974, 1977; Tan et al. 2011):

1. $g(\phi) = 0$, $g(X) = 1$ (boundary conditions)
2. If A, $B \subset P(X)$ and $A \subset B$, then $g(A) \leq g(B)$ (monotonicity)

A fuzzy measure has $2^m - 2$ parameters when $|X| = m$. This, along with bringing great powers of description to a fuzzy measure also introduces a problem of complexity (Grabisch et al. 2000). A λ-fuzzy measure g_λ is a special type of fuzzy measure which was introduced by Sugeno (1974). It is used to determine the values of fuzzy measures and gauge the relationship of criteria (Tan et al. 2011; Yang et al. 2008). It is the most widely used fuzzy measure (Yang et al. 2008), and its use avoids computational complexity in calculating the fuzzy measures using other more complex algorithms (Tan et al. 2011). The λ-fuzzy measure is constrained by a parameter λ which determines the degree of additivity among the criteria. If $A, B \subset X$ with $A \cap B = \phi$, an additional property satisfied by the λ-fuzzy measure is (Feng et al. 2010; Sugeno 1974; Yang et al. 2008):

$$g_\lambda(A \cup B) = g_\lambda(A) + g_\lambda(B) + \lambda \cdot g_\lambda(A) \cdot g_\lambda(B),$$
$$\text{where } \lambda \in (-1, \infty)$$

The fuzzy measure for any subset of X with only one element $g_\lambda(\{x_i\})$ is called fuzzy density, denoted as $g_i = g_\lambda(\{x_i\})$. The fuzzy measure $g_\lambda(X)$ can be formulated as

$$\begin{aligned} & g_\lambda(\{x_1, x_2, x_3, \ldots x_m\}) \\ & = \sum_{i=1}^{m} g_i + \lambda \sum_{i_1=1}^{m-1} \sum_{i_2=i_1+1}^{m} g_{i_1} \cdot g_{i_2} + \cdots + \lambda^{m-1} g_1 \cdot g_2 \ldots g_m \\ & = \frac{1}{\lambda} \left| \prod_{i=1}^{m} (1 + \lambda \cdot g_i) - 1 \right| \quad \text{for } -1 < \lambda < \infty \end{aligned} \tag{3}$$

Based on the equation above, because of the boundary condition $g_\lambda(X) = 1$, the unique solution for the parameter λ can be obtained from:

$$\lambda + 1 = \prod_{i=1}^{m} (1 + \lambda \cdot g_i) \tag{4}$$

Application of Eq. (3) with calculated λ values enables the calculation of a fuzzy measure of each subset of X (Chen and Cheng 2009). For the purpose of information aggregation, the fuzzy density g_i can be construed as a grade of importance of a criterion towards the final assessment. The fuzzy measure g_λ of any subset of X would therefore represent the grade of importance of a set of criteria towards the final evaluation (Laishram and Kalidindi 2009).

Let h be a measurable function from X to [0, 1] such that $h(x_1) \geq h(x_2), \ldots, \geq h(x_m)$, and g be a fuzzy measure (λ-fuzzy measure) on X. Here, h can be considered as the performance of a given criterion for the alternatives, whereas, g represents the grade of subjective importance of each criterion. Then the Choquet fuzzy integral (Feng et al. 2010; Grabisch 1996; Murofushi and Sugeno 1989; Sugeno 1974), i.e., the integral of all the performance assessments with respect to the associated grades of importance is given by

$$\begin{aligned} (c) \int h dg = & \, h(x_m) g(H_m) + [h(x_{m-1}) - h(x_m)] g(H_{m-1}) \\ & + \cdots + [h(x_1) - h(x_2)] g(H_1) \\ = & \, h(x_m)[g(H_m) - g(H_{m-1})] + h(x_{m-1})[g(H_{m-1}) \\ & - g(H_{m-2})] + \cdots + h(x_1) g(H_1) \end{aligned} \tag{5}$$

Here, $H_1 = \{x_1\}, H_2 = \{x_1, x_2\}, \ldots, H_m = \{x_1, x_2, \ldots, x_m\} = X$. Hence, the calculation of the Choquet fuzzy integral with respect to λ-fuzzy measure requires information on fuzzy densities g_i (fuzzy measures of the singletons) and values of $h(x_i)$ (Chiang 1999).

Table 2. Background information on the respondent experts

Attribute	Categorization	Number of respondents
Sector	Public	35
	Private	55
Years of experience (working and/or research in PPPs)	Less than or equal to 5	47
	6–10	21
	11–15	12
	16–20	7
	21 and above	3
Area/sector of expertise	Power	34
	Transport	48
	Both	8

Data Analysis and Results

The data collected from the questionnaire survey were subject to various tests using Microsoft Excel 2015 and Statistical Package for Social Science (SPSS) version 23.0. These include fuzzy risk analysis and normalization analysis to select critical factors, FA to group correlated factors, and fuzzy measure and Choquet fuzzy integral analysis to determine sectoral and case-specific risk levels of identified CRGs and ORI. The experts that participated in the research had rich experience in handling transactions in power and transport infrastructure PPP projects. In total, 90 valid responses were collected through various mediums out of the total 140 experts who were initially contacted and who agreed to participate (Table 2).

Risk Analysis

Because the industry experts assessed the risk factors on linguistic terms, there was a need to convert these linguistic assessments to quantitative form by using fuzzy numbers, before performing any further analysis. The linguistic terms assigned to rate degree of likelihood (probability) and severity of risks by each respondent were first converted to the corresponding fuzzy numbers (Table 1), and then these ratings were aggregated over all the respondents, using Eq. (1), to obtain average aggregate fuzzy probability and severity for each risk factor. Further, to calculate the risk impact which is given by $(probability \times severity)^{1/2}$ (Ameyaw and Chan 2015a, b; Xu et al. 2010), the product of aggregate probability and severity values was assessed using fuzzy arithmetic operation $\otimes$, and then the square root of the resulting fuzzy number was computed before defuzzifying to a crisp value, using Eq. (2). The complete analysis with rankings is shown in Table 3. The table shows risk rankings for each sector (power and transport infrastructure) and for combined analysis.

Combined analysis shows that five risk factors: delay in financial closure, land acquisition, financing risk, delay in project approvals and permits, and poor public decision-making process, have a *high* risk impact rating of 0.600 and above (according to Zhao et al. (2013), it is interpreted by referring to any linguistic term in Table 1 that provides the highest membership to the assessed risk impact value), whereas 40 risk factors have an impact rating of 0.400 or above which can be linguistically expressed as *moderate* impact at the least. At the sectoral level, for the power infrastructure projects, only four risks exhibit an impact rating of 0.600 and above including delay in financial closure, delay in project approvals and permits, payment risk, and financing risk, whereas another 38 risk factors achieved an impact rating of at least 0.400 (interpreted as at least *moderate*). For transport infrastructure projects, six risk factors with impact ratings equal to 0.600 and above include land acquisition, financing risk, unfavorable national/international economy, delay in financial closure, construction risk, and poor

Table 3. Overall and sectoral risk analysis

		Overall					Power sector		Transport sector	
Identifier	Risk factors	Fuzzy aggregated P_r	Fuzzy aggregated S_r	I_r	R	N	I_r	R	I_r	R
RF_09	Delay in financial closure	(0.463,0.633,0.788)	(0.533,0.701,0.832)	0.657	1	1	0.709	1	0.614	4
RF_27	Land acquisition	(0.39,0.554,0.708)	(0.573,0.739,0.861)	0.631	2	0.918	0.586	7	0.654	1
RF_08	Financing risk	(0.385,0.562,0.728)	(0.551,0.711,0.840)	0.625	3	0.900	0.615	4	0.644	2
RF_30	Delay in project approvals and permits	(0.389,0.561,0.721)	(0.482,0.660,0.813)	0.602	4	0.828	0.625	2	0.576	9
RF_03	Poor public decision-making process	(0.411,0.585,0.742)	(0.461,0.630,0.775)	0.600	5	0.821	0.585	8	0.604	6
RF_28	Construction risk	(0.381,0.556,0.724)	(0.468,0.646,0.794)	0.593	6	0.799	0.595	6	0.607	5
RF_01	Government intervention	(0.363,0.527,0.685)	(0.487,0.651,0.786)	0.580	7	0.759	0.597	5	0.553	12
RF_36	Procurement risk	(0.342,0.515,0.682)	(0.451,0.624,0.783)	0.564	8	0.708	0.534	13	0.588	7
RF_25	Inability of debt service	(0.257,0.426,0.604)	(0.572,0.739,0.862)	0.555	9	0.680	0.524	14	0.576	9
RF_05	Inflation	(0.425,0.603,0.758)	(0.343,0.511,0.677)	0.551	10	0.668	0.514	15	0.585	8
RF_18	Payment risk	(0.329,0.480,0.646)	(0.481,0.633,0.765)	0.551	10	0.668	0.62	3	0.483	26
RF_39	Planning risk	(0.301,0.463,0.629)	(0.464,0.635,0.789)	0.540	12	0.633	0.497	20	0.567	11
RF_16	Pricing and toll/tariff review uncertainty	(0.318,0.475,0.639)	(0.445,0.616,0.770)	0.539	13	0.630	0.549	10	0.532	17
RF_40	Change in government and political opposition	(0.339,0.505,0.673)	(0.412,0.577,0.722)	0.537	14	0.624	0.548	11	0.520	19
RF_17	Unfavorable national/international economy	(0.316,0.488,0.660)	(0.421,0.585,0.743)	0.533	15	0.611	0.473	26	0.625	3
RF_43	Design and construction deficiencies	(0.267,0.431,0.600)	(0.473,0.639,0.786)	0.522	16	0.577	0.488	23	0.545	13
RF_20	Availability/performance risk	(0.244,0.405,0.583)	(0.501,0.666,0.811)	0.519	17	0.567	0.508	18	0.533	16
RF_07	Variation in foreign exchange rate and convertibility issues	(0.383,0.544,0.705)	(0.335,0.492,0.651)	0.518	18	0.564	0.555	9	0.500	20
RF_23	Operation cost overrun	(0.314,0.483,0.652)	(0.386,0.557,0.708)	0.515	19	0.555	0.506	19	0.541	14
RF_41	Political violence/government instability	(0.253,0.411,0.584)	(0.473,0.632,0.775)	0.509	20	0.536	0.511	17	0.487	23
RF_06	Interest rate fluctuation	(0.341,0.508,0.679)	(0.344,0.503,0.675)	0.508	21	0.533	0.483	25	0.540	15
RF_37	Corruption	(0.313,0.469,0.639)	(0.372,0.558,0.665)	0.502	22	0.514	0.544	12	0.463	29
RF_44	Development risk	(0.287,0.447,0.618)	(0.376,0.540,0.694)	0.492	23	0.483	0.49	22	0.485	24
RF_13	Imperfect law and supervision system	(0.256,0.419,0.587)	(0.392,0.557,0.711)	0.482	24	0.451	0.466	27	0.482	27
RF_33	Lack of supporting infrastructure/utilities	(0.29,0.456,0.625)	(0.337,0.504,0.676)	0.481	25	0.448	0.511	16	0.446	34
RF_11	Change in law/regulation	(0.249,0.414,0.584)	(0.399,0.560,0.706)	0.480	26	0.445	0.493	21	0.449	32
RF_34	Organization and coordination risk	(0.299,0.465,0.635)	(0.316,0.486,0.660)	0.477	27	0.436	0.446	28	0.490	22
RF_38	Latent defect risk	(0.244,0.411,0.585)	(0.374,0.550,0.719)	0.475	28	0.429	0.432	30	0.523	18
RF_12	Conflicting or imperfect contract	(0.230,0.390,0.563)	(0.383,0.556,0.714)	0.465	29	0.398	0.427	32	0.492	21
RF_35	Force majeure	(0.200,0.358,0.535)	(0.424,0.592,0.743)	0.461	30	0.386	0.42	34	0.482	27
RF_32	Unforeseen weather/geotechnical conditions	(0.221,0.386,0.560)	(0.367,0.538,0.705)	0.456	31	0.370	0.434	29	0.443	35
RF_26	Environmental damage risk	(0.278,0.431,0.598)	(0.293,0.449,0.617)	0.444	32	0.332	0.416	35	0.454	30
RF_31	Design/construction/operation changes	(0.232,0.389,0.558)	(0.336,0.503,0.668)	0.444	32	0.332	0.428	31	0.447	33
RF_02	Quasicommercial risk	(0.203,0.337,0.502)	(0.417,0.555,0.687)	0.437	34	0.310	0.483	24	0.387	41
RF_19	Public opposition	(0.231,0.383,0.555)	(0.325,0.481,0.648)	0.434	35	0.301	0.391	39	0.454	30
RF_45	Lack of skilled experts	(0.198,0.359,0.533)	(0.343,0.516,0.683)	0.432	36	0.295	0.423	33	0.443	35
RF_42	Supply, input or resource risk	(0.171,0.33,0.51)	(0.359,0.533,0.707)	0.423	37	0.266	0.408	36	0.438	37
RF_15	Change in market demand	(0.215,0.365,0.533)	(0.324,0.485,0.637)	0.422	38	0.263	0.357	42	0.485	24
RF_10	Insurance risk	(0.22,0.379,0.555)	(0.275,0.45,0.629)	0.417	39	0.248	0.405	37	0.413	38
RF_14	Competition risk	(0.214,0.363,0.531)	(0.29,0.451,0.622)	0.409	40	0.223	0.404	38	0.408	39
RF_22	Technology risk	(0.185,0.334,0.508)	(0.269,0.421,0.587)	0.381	41	0.135	0.382	40	0.391	40
RF_21	Residual asset value on transfer to the government	(0.2,0.356,0.53)	(0.231,0.39,0.56)	0.378	42	0.125	0.359	41	0.370	42
RF_24	Archaeological discovery/cultural heritage	(0.127,0.25,0.422)	(0.349,0.497,0.659)	0.363	43	0.078	0.326	45	0.351	44
RF_29	Material/labor shortage or nonavailability	(0.124,0.268,0.442)	(0.273,0.438,0.616)	0.349	44	0.034	0.344	43	0.346	45
RF_04	Expropriation/nationalization of assets	(0.072,0.176,0.342)	(0.478,0.621,0.73)	0.338	45	0.000	0.331	44	0.360	43

Note: P_r = risk probability; S_r = risk severity; I_r = impact; R = rank; and N = normalized value.

public decision-making process. In addition, another 39 risk factors achieved a risk impact rating of 0.400 and above. The top ranking risk factors relate to institutional capacity (United Nations Economic Commission for Europe 2008) and economic issues that characterize the state of affairs of developing countries around the world (also evident from the literature review above).

The risk factors' impact ratings were further normalized to identify the most critical risk factors for development of the risk assessment model, as undertaken by Ameyaw and Chan (2015b). A total of 22 risk factors were obtained as the overall most significant with normalized values of 0.5 and above (Table 3), that were later utilized to develop the risk assessment model.

Model Development and Its Application

Risks Categorization

To obtain the independent common factors (CRGs), as mentioned previously, crisp risk impact values, evaluated from defuzzified attribute ratings obtained from each respondent expert were utilized as inputs for the FA. The KMO value obtained was 0.663 which is greater than the minimum acceptable value of 0.5 (Field 2005). Bartlett's test of sphericity confirmed the rejection of null hypothesis with a value of 523.830 at a p-value of 0.000 (Norusis 2003). A clean solution was obtained with a seven-factor model, herein called the CRGs. The first four factors are interpreted as *project planning and implementation*, *country economy*, *public sector maturity*, and *project revenue*, each of which has multiple constituent interrelated risk factors. The remaining three extracted factors are interpreted as *project finance*, *political stability*, and *government interference*, which consist of one risk factor each. Total cumulative variance explained by the model amounts to 84.354% (Table 4). The structure obtained from the FA primarily lends itself in creating independent factors that serve as input variables for the determination of the sectoral ORI and that of the case study project. In addition, the established CRGs also enable determination of risk index values at the group level that may assist in informing and guiding better management of risks.

Case Study: Risk Assessment of a Motorway BOT Project

Data for a case study project were collected from experts and analyzed to determine the risk index of various risk groups and the overall project using the methodology discussed below. The project is a part of a 1,100 km long high-speed controlled access modern motorway. At the time of collecting data for this research, the case study project (which is one of the several sections) was in the tendering phase. The project section under consideration spans more than approximately 300 km with multiple bridges, interchanges, and underpasses included in its scope and is expected to cost close to USD 2 billion according to the latest estimates. The project is being implemented on the BOT basis with a lease period of 18 years. Experts from multiple bidding consortia were contacted, and three individuals from the private sector, having working knowledge of the project, agreed to participate. The experts were requested to evaluate the critical risk factors in terms of assessment based on individual risk's probability and severity. This was to be done based on experience of the respondents of working on

Table 4. Factor analysis results and sectoral and case study risk attributes values

Factor group	Percentage of variance explained	Factor loading	Risk attributes (power)		Risk attributes (transport)		Risk attributes (case study)	
			P_r	S_r	P_r	S_r	P_r	S_r
CRG-1 Project planning and implementation	43.904							
RF_23		0.852	0.456	0.563	0.525	0.557	0.561	0.683
RF_39		0.812	0.434	0.570	0.479	0.674	0.439	0.622
RF_37		0.798	0.518	0.573	0.430	0.499	0.617	0.622
RF_28		0.777	0.563	0.629	0.569	0.649	0.678	0.794
RF_36		0.722	0.488	0.586	0.510	0.678	0.378	0.561
RF_43		0.637	0.414	0.577	0.442	0.676	0.439	0.794
RF_27		0.530	0.537	0.640	0.557	0.770	0.500	0.678
RF_20		0.451	0.394	0.658	0.407	0.703	0.500	0.622
CRG-2 Country economy	11.454							
RF_06		0.860	0.488	0.478	0.527	0.553	0.561	0.561
RF_05		0.835	0.566	0.467	0.619	0.552	0.683	0.561
RF_07		0.832	0.560	0.549	0.539	0.463	0.678	0.561
CRG-3 Public sector maturity	9.504							
RF_03		0.812	0.573	0.598	0.581	0.629	0.739	0.561
RF_09		0.771	0.680	0.740	0.597	0.631	0.794	0.739
RF_16		0.503	0.482	0.627	0.467	0.607	0.378	0.500
RF_40		0.462	0.527	0.570	0.493	0.550	0.439	0.561
RF_30		0.326	0.592	0.661	0.515	0.644	0.617	0.622
CRG-4 Project revenue	6.319							
RF_18		0.940	0.547	0.703	0.407	0.574	0.439	0.739
RF_17		0.694	0.423	0.530	0.572	0.683	0.561	0.683
RF_25		0.579	0.402	0.689	0.446	0.750	0.439	0.733
CRG-5 Project finance	4.651							
RF_08		0.694	0.536	0.707	0.571	0.728	0.739	0.794
CRG-6 Political stability	4.594							
RF_41		0.789	0.411	0.638	0.398	0.600	0.378	0.561
CRG-7 Government interference	3.928							
RF_01		0.919	0.548	0.652	0.483	0.633	0.711	0.561

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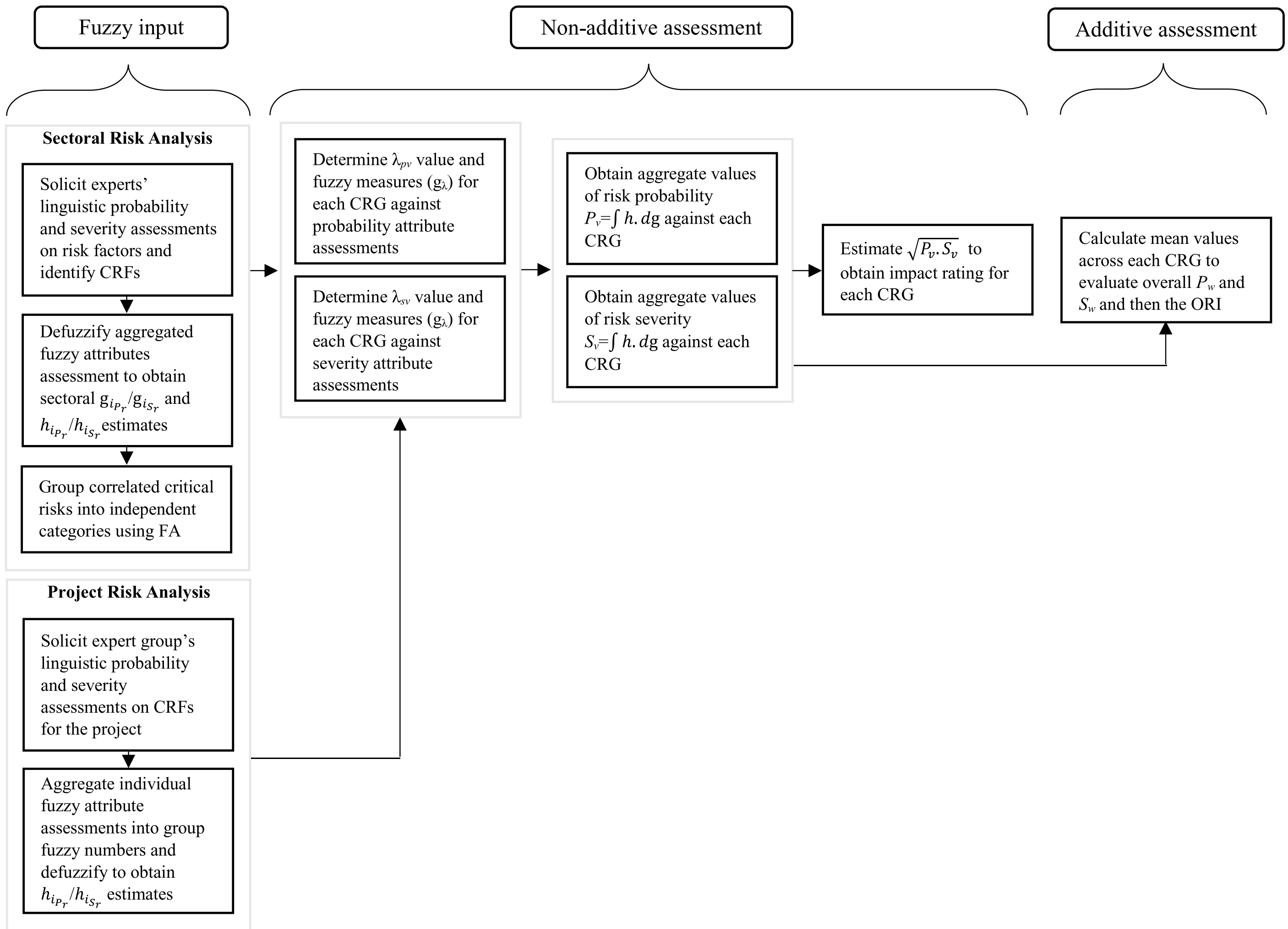

Fig. 1. Fuzzy risk assessment model.

projects in Pakistan and their perception on critical risk factors related to the project.

Stepwise Development and Application of the Model

To setup and demonstrate the model application, a stepwise procedure has been delineated in Fig. 1. Because assessment of ORI is akin to a multiattribute decision-making problem, as mentioned previously, the idea is to obtain two types of information for each risk factor against each attribute of risk probability and severity. The grades of importance/weightings (g_i) of the factors need to be estimated along with the performance ratings of these factors (h) to assess risk level in the sectoral and/or project-specific context. Because four of the CRGs are comprised of multiple risk factors, fuzzy measure and Choquet fuzzy integral analysis were performed for these CRGs to accommodate factor interactions, whereas, obviously, no such consideration was necessary for the remaining CRGs. With independence among CRGs, an additive measure was adopted for aggregation to compute ORI (Liou and Tzeng 2007). In this paper, both sectoral and project-level applications of the model have been presented. The attribute data on each risk for sectoral and case study project analysis (Table 4) were processed to determine the risk index of each CRG and the ORI as follows:

1. Identify critical risk factors—CRFs for PPP infrastructure projects were identified through a questionnaire survey of public and private sector stakeholders in a countrywide data collection effort (Table 3).
2. Identify CRGs to group correlated factors—FA was performed on CRFs to group risk factors that exhibit significant correlation and to obtain uncorrelated CRGs (Table 4). In total, seven CRGs were obtained.
3. Evaluate the grade of importance of individual CRFs—The grade of importance/weightings labelled as g_{iP_r}/g_{iS_r} were determined through risk attribute assessments of CRFs in the survey. The subscripts were defined to designate fuzzy density values for any CRF i, under a CRG v, for each of the attributes of probability (P_r) and severity (S_r). The defuzzified aggregated values of both the risk attributes for each individual risk were used for that purpose (Table 4) (Ameyaw and Chan 2015b; Wang et al. 2010).
4. Assess fuzzy measures (g_λ)
   a. To obtain the aggregate assessment of risk attributes (P_v/S_v), a λ value was calculated for each CRG against each attribute; hence, two sets (one for each infrastructure sector) of eight λ values ($\lambda_{p1}-\lambda_{p4}$, $\lambda_{s1}-\lambda_{s4}$) were calculated. The λ values were calculated by inserting fuzzy densities (g_{iP_r}/g_{iS_r}) in Eq. (4). For example, for transport infrastructure projects, λ_{p4} (−0.7139) for CRG-4 (Project revenue), was assessed as

$$(1+0.407\lambda_{p4})*(1+0.572\lambda_{p4})*(1+0.446\lambda_{p4})=(1+\lambda_{p4})$$

Table 5. Case study λ and fuzzy measure (g_λ) analysis: probability

Identifier	$h_{i_{P_r}}$	Fuzzy measure	g_λ
CRG-1 ($\lambda_{p1} = -0.9955$)			
RF_28	0.678	$g_\lambda(x_{RF\_28})$	0.569
RF_37	0.617	$g_\lambda(x_{RF\_28}, x_{RF\_37})$	0.755
RF_23	0.561	$g_\lambda(x_{RF\_28}, x_{RF\_37}, x_{RF\_23})$	0.886
RF_27	0.500	$g_\lambda(x_{RF\_28}, x_{RF\_37}, x_{RF\_23}, x_{RF\_27})$	0.952
RF_20	0.500	$g_\lambda(x_{RF\_28}, x_{RF\_37}, x_{RF\_23}, x_{RF\_27}, x_{RF\_20})$	0.973
RF_39	0.439	$g_\lambda(x_{RF\_28}, x_{RF\_37}, x_{RF\_23}, x_{RF\_27}, x_{RF\_20}, x_{RF\_39})$	0.988
RF_43	0.439	$g_\lambda(x_{RF\_28}, x_{RF\_37}, x_{RF\_23}, x_{RF\_27}, x_{RF\_20}, x_{RF\_39}, x_{RF\_43})$	0.995
RF_36	0.378	$g_\lambda(x_{RF\_28}, x_{RF\_37}, x_{RF\_23}, x_{RF\_27}, x_{RF\_20}, x_{RF\_39}, x_{RF\_43}, x_{RF\_36})$	1.000
CRG-2 ($\lambda_{p2} = -0.8651$)			
RF_05	0.683	$g_\lambda(x_{RF\_05})$	0.619
RF_07	0.678	$g_\lambda(x_{RF\_05}, x_{RF\_07})$	0.870
RF_06	0.561	$g_\lambda(x_{RF\_05}, x_{RF\_07}, x_{RF\_06})$	1.000
CRG-3 ($\lambda_{p3} = -0.9744$)			
RF_09	0.794	$g_\lambda(x_{RF\_09})$	0.597
RF_03	0.739	$g_\lambda(x_{RF\_09}, x_{RF\_03})$	0.840
RF_30	0.617	$g_\lambda(x_{RF\_09}, x_{RF\_03}, x_{RF\_30})$	0.933
RF_40	0.439	$g_\lambda(x_{RF\_09}, x_{RF\_03}, x_{RF\_30}, x_{RF\_40})$	0.978
RF_16	0.378	$g_\lambda(x_{RF\_09}, x_{RF\_03}, x_{RF\_30}, x_{RF\_40}, x_{RF\_16})$	1.000
CRG-4 ($\lambda_{p4} = -0.7139$)			
RF_17	0.561	$g_\lambda(x_{RF\_17})$	0.572
RF_18	0.439	$g_\lambda(x_{RF\_17}, x_{RF\_18})$	0.813
RF_25	0.439	$g_\lambda(x_{RF\_17}, x_{RF\_18}, x_{RF\_25})$	1.000

b. For the general sectoral evaluation (power/transport) of risk level, attribute values $h_{i_{P_r}}/h_{i_{S_r}}$ on component risks were derived from respondents' ratings of probability (P_r) and severity (S_r) (crisp values) in the survey, whereas for the case study analysis, $h_{i_{P_r}}/h_{i_{S_r}}$ ratings were calculated using crisp values of risk attributes that were specifically assessed by the experts to reflect the perceptions regarding the project only (Table 4).

c. The λ values were then utilized to obtain the values of fuzzy measure g_λ for each subset of risk factors under the CRGs, for both risk attributes, separately. Before calculating g_λ, the risk attributes ratings $h_{i_{P_r}}/h_{i_{S_r}}$ are required to be rearranged to enable application of the methodology for the calculation of fuzzy measures and fuzzy integral using Eqs. (3) and (5).

d. Because the λ values explain interaction between factors, λ values obtained for transport sector analysis were also used for determining the fuzzy measures for the case study analysis (Tables 5 and 6). Here, only the case study analysis is shown while omitting detailed calculations of the sectoral fuzzy measure evaluations due to limitation of space.

5. Evaluate risk level/index of CRGs using Choquet fuzzy integral—For both sectoral and case study analysis, the Choquet fuzzy integral was applied to compute the aggregate probability and severity values for each CRG ($P_1 - P_4/S_1 - S_4$), using Eq. (5) (Table 7). To demonstrate the calculation procedure, the aggregate probability value for CRG-4 for the case study project was assessed as follows:

$$\begin{aligned} P_4 &= h(x_{RF\_25}) \cdot g_\lambda(x_{RF\_17}, x_{RF\_18}, x_{RF\_25}) \\ &\quad + [h(x_{RF\_18}) - h(x_{RF\_25})] \cdot g_\lambda(x_{RF\_17}, x_{RF\_18}) \\ &\quad + [h(x_{RF\_17}) - h(x_{RF\_18})] \cdot g_\lambda(x_{RF\_17}) \\ &= 0.439 * 1 + (0.439 - 0.439) * 0.813 \\ &\quad + (0.561 - 0.439) * 0.572 = 0.509 \end{aligned}$$

Risk impact values for each CRG (I_1–I_7) were also computed by taking the square root of the product of risk probability and severity $\sqrt{P_v * S_v}$ at CRG level (Table 7).

6. Calculate the overall risk attributes value and obtain ORI—Because the factor groups obtained from FA can be assumed to be independent, the arithmetic mean was employed to obtain the requisite overall probability (P_w) and severity (S_w) values. Risk Impact (I_w) or the ORI was calculated through $\sqrt{P_w * S_w}$ (Table 7).

Discussion

The aggregate risk attribute score, obtained through fuzzy measure and the Choquet fuzzy integral approach for each CRG of sectoral and case study analysis are shown in Table 7. The ORI can be converted back into a representative linguistic expression for risk assessment by determining the linguistic term that provides the highest membership at the ORI value according to Table 1. In that sense, both the power and transport infrastructure sectors exhibit a *moderate* level (Fig. 2) of risk when considering investment in these sectors. Further examining the risk impact indices of factor groups, it is evident that at the sectoral level, the situation is quite different. For power infrastructure projects, *public sector maturity* was rated as the only CRG at *high* risk level, whereas *project planning and implementation*, *project finance*, *project revenue*, and *public sector maturity*, were all rated as *high* risk CRGs for transport infrastructure projects. One possible explanation to this effect can be the fact that investment in transport infrastructure PPP projects has a young history in Pakistan as opposed to the power sector where the private investment started in the early 1990's (Mazher et al. 2017). The remaining CRGs in each sector were rated at a *moderate* risk level thus suggesting that all the CRGs are in fact significant and demand attention by the stakeholders.

Factor group one represents risk factors that spread over the project lifecycle including planning and design, construction, and operation and maintenance phase. The eight factors in this category capture the uncertainty in ability of the stakeholders, both the public and the private sectors, in terms of not being able to execute their responsibilities properly. The highest ranking risk factor in this category has different criticality for the power and transport

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Table 6. Case study λ and fuzzy measure (g_λ) analysis: Severity

Identifier	$h_{i_{S_r}}$	Fuzzy measure	g_λ
CRG-1 ($\lambda_{s1} = -0.9998$)			
RF_43	0.794	$g_\lambda(x_{RF\_43})$	0.676
RF_28	0.794	$g_\lambda(x_{RF\_43}, x_{RF\_28})$	0.886
RF_27	0.683	$g_\lambda(x_{RF\_43}, x_{RF\_28}, x_{RF\_27})$	0.974
RF_23	0.678	$g_\lambda(x_{RF\_43}, x_{RF\_28}, x_{RF\_27}, x_{RF\_23})$	0.989
RF_20	0.622	$g_\lambda(x_{RF\_43}, x_{RF\_28}, x_{RF\_27}, x_{RF\_23}, x_{RF\_20})$	0.997
RF_36	0.622	$g_\lambda(x_{RF\_43}, x_{RF\_28}, x_{RF\_27}, x_{RF\_23}, x_{RF\_20}, x_{RF\_36})$	0.999
RF_37	0.622	$g_\lambda(x_{RF\_43}, x_{RF\_28}, x_{RF\_27}, x_{RF\_23}, x_{RF\_20}, x_{RF\_36}, x_{RF\_37})$	0.999
RF_39	0.561	$g_\lambda(x_{RF\_43}, x_{RF\_28}, x_{RF\_27}, x_{RF\_23}, x_{RF\_20}, x_{RF\_36}, x_{RF\_37}, x_{RF\_39})$	1.000
CRG-2 ($\lambda_{s2} = -0.8084$)			
RF_06	0.561	$g_\lambda(x_{RF\_06})$	0.553
RF_05	0.561	$g_\lambda(x_{RF\_06}, x_{RF\_05})$	0.858
RF_07	0.561	$g_\lambda(x_{RF\_06}, x_{RF\_05}, x_{RF\_07})$	1.000
CRG-3 ($\lambda_{s3} = -0.9907$)			
RF_09	0.739	$g_\lambda(x_{RF\_09})$	0.631
RF_40	0.622	$g_\lambda(x_{RF\_09}, x_{RF\_40})$	0.837
RF_30	0.561	$g_\lambda(x_{RF\_09}, x_{RF\_40}, x_{RF\_30})$	0.947
RF_16	0.561	$g_\lambda(x_{RF\_09}, x_{RF\_40}, x_{RF\_30}, x_{RF\_16})$	0.985
RF_03	0.500	$g_\lambda(x_{RF\_09}, x_{RF\_40}, x_{RF\_30}, x_{RF\_16}, x_{RF\_03})$	1.000
CRG-4 ($\lambda_{s4} = -0.9556$)			
RF_25	0.739	$g_\lambda(x_{RF\_25})$	0.750
RF_18	0.733	$g_\lambda(x_{RF\_25}, x_{RF\_18})$	0.913
RF_17	0.683	$g_\lambda(x_{RF\_25}, x_{RF\_18}, x_{RF\_17})$	1.000

Table 7. Sectoral and case study CRG and overall risk ratings

		Power sector				Transport sector				Case study			
Identifier	Group description	P_v	S_v	I_v	Rank	P_v	S_v	I_v	Rank	P_v	S_v	I_v	Rank
CRG-1	Project planning and implementation	0.543	0.648	0.570	4	0.554	0.753	0.646	1	0.629	0.781	0.701	3
CRG-2	Country economy	0.553	0.515	0.514	6	0.587	0.540	0.563	5	0.666	0.561	0.611	5
CRG-3	Public sector maturity	0.647	0.716	0.652	1	0.578	0.638	0.607	4	0.739	0.685	0.712	2
CRG-4	Project revenue	0.487	0.689	0.554	5	0.512	0.728	0.610	3	0.509	0.733	0.611	5
CRG-5	Project finance	0.536	0.707	0.593	2	0.571	0.728	0.645	2	0.739	0.794	0.766	1
CRG-6	Political stability	0.411	0.638	0.494	7	0.398	0.600	0.489	7	0.378	0.561	0.460	7
CRG-7	Government interference	0.548	0.652	0.576	3	0.483	0.633	0.553	6	0.711	0.561	0.632	4
ORI		0.5891				0.5893				0.6459			

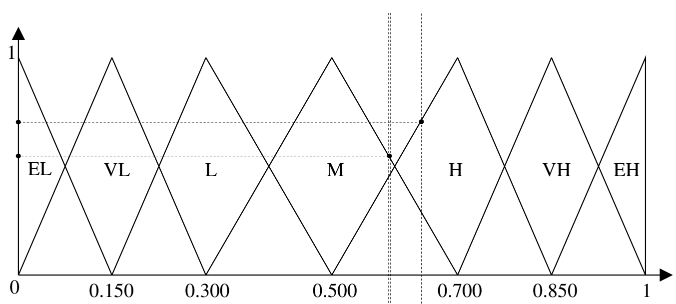

Fig. 2. Linguistic interpretation of ORI.

infrastructure sectors because acquiring right of way for a toll road is more difficult than acquiring a parcel of land due to issues of multiple ownership and the complex negotiations (PPIAF 2009). Land acquisition is the responsibility of the government (State Bank of Pakistan 2007). Poor governance (lengthy procedures and late payments to the land owners) usually results in delays and extra costs. Soomro and Zhang (2011) cited conflicts and differences between the central and provincial governments regarding land ownership and privatization, as one of the reasons that led to cancellation of the M9 motorway project concession. Construction risk, rated *high* for transport infrastructure projects, is considered significant because construction phase is the most investment intensive phase of the project due to the characteristically large capital costs. Any delays or overruns can be devastating, because delays can disturb project cash flow, thus resulting in penalties in the form of additional interest payments, increase in project cost due to effects of inflation, and may necessitate arrangement of additional finance, should the need arise. Factor group two accommodates risk factors that are directly influenced by the dynamics of the project's host country economy. Inflation, variation in interest, and foreign exchange rate directly impact project cost and profitability. A relatively lower perception of inflation in the power sector as opposed to the transport infrastructure projects may be explained by the way it is treated in both the sectors. For power sector projects, the effects of inflation are adjusted periodically on actual basis in the price of the electricity sold to the utilities, which is different from transport infrastructure projects where effects of inflation must be forecasted and built into the toll tax schedule for the entire concession period as being practiced on some projects. Risk related to foreign exchange is more critical to power than transport infrastructure projects because the majority of the plant equipment and instrumentation is imported in foreign currency, which constitutes a bulk of the total project investment. Furthermore, if the prices are denominated in local currency while financing and other obligations (loan payment commitments and purchase of project resources such as fuel or equipment) must be met in other currencies (United Nations Commission on International Trade Law 2001), foreign exchange risk becomes a concern for as long as the obligations are not completely met. The third factor group dealing with the public sector's capacity and commitment towards procuring and operating PPP projects emphasizes the need to streamline processes and procedures and to adopt best practices. Delay in financial closure, the top-ranking risk factor of this group, is dependent upon a number of factors such as bankability of the project, which is in turn determined by project demand, government support, and timely acquisition of land and the requisite permits/clearances. These issues are significantly influenced by government policy and cooperation (Thomas et al. 2003). Whereas these issues are applicable for Pakistan as well, delays can be avoided if the concerned public authorities can reduce uncertainties by conducting project feasibility studies, acquiring project land, obtaining project approvals/permits early, and selecting strong private sponsors for the project. Furthermore, projects may simply be costing more because the bidders have to add hefty contingency margins to cover change in component costs, owing to long-time duration between bid submission and subsequent financial close and startup of the project. The risk of a poor public decision-making process is evident from a low level of operational maturity of Pakistan among Asian-Pacific countries (Economist Intelligence Unit 2015), lack of PPP capacity in provincial governments (Asian Development Bank 2015), and as mentioned earlier, long and protracted procedures in acquisition of land, permits, and approvals. Factor group four deals with risk factors that relate to the project's ability to generate sufficient revenue. For the power sector, lack of or delayed payments by the power purchaser (Economist Intelligence Unit 2015) strains the power producers' ability to operate the plant and also to pay off debt. A poor local economy may aggravate the problem due to lowering demand and defaulting consumers thus resulting in problems for the power purchaser to make payments. A poor economy may also render the government unable to honor its guarantees (Xenidis and Angelides 2005). For the transport infrastructure projects, payment risk may not be a big problem because potential consumers may only be able to use the facility upon paying a predetermined toll tax. However, a poor economy may significantly influence travel patterns, thus hitting hard on demand and the ability to pay off debts in time. Furthermore, unlike the power sector, transport sector projects do not carry demand guarantees for most of the projects in operation in the country, therefore, possibly making the inability of debt service a relatively higher perceived risk.

Factor groups five, six, and seven independently account for financing risk, political violence/government instability, and government intervention, respectively. Both financing risks and government intervention were ranked among the top 10 factors for power and transport infrastructure projects in China (Cheung and Chan 2011). Government intervention is mostly seen as a prefinancial closure risk for PPP projects in both sectors (in Pakistan) where intervention in the form of changing policies/project requirements is primarily seen as a problem resulting in delays and potentially extra cost. An example of this occurred when the government banned procurement of privately funded power projects that depended on imported fuel, influencing several projects in the development stage (Bhutta 2017). Raising finances for PPP projects can be a problem because only short- to medium-term financing is available from commercial banks due to lack of debt market maturity (Asian Development Bank 2015). Furthermore, the creditworthiness of the potential sponsor is also important for securing loans (Xenidis and Angelides 2005). Noor (2011) reported an unstable political scenario and law and order/security situation among the barriers to implementation of modern project procurement method and systems in Pakistan, which led to a lack of investor interest, both domestic and foreign. This risk ranked higher for power infrastructure projects with an impact value of 0.511 (ranked 17th) as opposed to the transport infrastructure projects that recorded a perceived impact of 0.487 (ranked 23rd). This may be explained by the fact that most of the investment in large power projects is foreign, whereas it is local for the transport sector projects. However, this may be changing because of the rapid rise in private investments in both infrastructure sectors (Mazher et al. 2017).

Looking at the case study project, the experts' assessment of risks conclusively put all the CRGs at *high* risk rating except the *political stability* CRG which is rated as *moderate*, with the ORI at 0.6459 that is interpreted as *high*. A possible explanation for this may be the fact that the case study project is the largest BOT transport infrastructure project investment in the country's history. Also, at the same time, it is reassuring to see that the *political stability* CRG obtained a *moderate* rating suggesting a lower level of concern potentially owing to the improvement in the political and security arena. All in all, the analysis shows that under the existing circumstances, both the public and private sectors need to execute meticulous risk management efforts while considering development and promotion of PPP infrastructure projects in Pakistan.

Model Test Process

Following the procedure adopted to test the developed model in Zayed et al. (2008), this research also employed a convergent validation method to establish the robustness of the proposed model. A questionnaire was developed based on 22 CRFs and sent to highway PPP experts in Pakistan to obtain project-specific assessment of the CRFs. The questionnaire also solicited holistic risk evaluation for the project, as a whole, based on the perceptions of the experts and their experience of having worked on the project. The risks were assessed using the linguistic terms (Table 1), whereas the holistic evaluation was also made using the same terms. In total, five projects worth of risk assessment data were received from five highway PPP experts. Each expert evaluated the risks and provided a holistic risk evaluation for a project on which they had recently worked. The procedure adopted for case-study analysis (mentioned above) was used to assess the ORI for the five projects. The calculated ORIs, their corresponding linguistic approximations (Table 1), and the holistic linguistic risk evaluations are shown in Table 8. It is evident that the proposed model performed satisfactorily in approximating the experts' overall evaluation. Furthermore, the ranking obtained for the projects using the proposed methodology is similar to the ranking based on holistic risk evaluation.

Conclusions and Recommendations

Chan et al. (2011) classified PPP risks into systematic/country risks (political, economic, legal, social, and natural risks) and specific project risks (construction, operation, market, relationship, and other risks). Comparison of the top 10 ranked risk factors reported here with top ranked risks in research coming out of developing countries such as China, Nigeria, and Ghana (Chan et al. 2011; Ibrahim et al. 2006; Osei-Kyei and Chan 2017) shows a greater significance of systematic/country risks. This is different from developed countries or regions where specific project risks tend to be more significant among the top 10 risks, as reported in Akintoye et al. (1998) and Osei-Kyei and Chan (2017) for the United Kingdom

Table 8. Holistic and model based risk evaluation

Projects	Holistic evaluation	Proposed model	
		ORI	Linguistic approximation
B	VH	0.762	H
E	VH	0.751	H
D	H	0.738	H
A	H	0.734	H
C	M	0.711	H

and Hong Kong, respectively. Risk management research from Greece (Roumboutsos and Anagnostopoulos 2008) and Singapore (Hwang et al. 2013) (although developed regions) shows a similar trend to developing countries with a higher prevalence of systematic/country risks. A review of top ranking systematic/country risks of these jurisdictions (including Pakistan) suggests that both PPP implementation and operational maturity of countries may also play an important role in determining project riskiness, in addition to the developing or developed status of a country. According to the United Nations Economic Commission for Europe (2008), the effects of lack of well performing institutions in many countries manifest as unusually lengthy negotiations between the public and private partners, slow closures of projects, inflexible risk sharing, and wasted resources as a result of project cancellations. In PPP contracts, many systematic/country risks and some project-specific risks are preferred to be allocated to the public sector (Chan et al. 2011; Ke et al. 2010). Thus, an important implication of higher significance of systematic/country risks in developing countries (or those with low PPP implementation and operational maturity) is that the governments should be vigilant in controlling these risks. This is also important due to the fact that several project risks are interrelated (Dey and Ogunlana 2004; Loosemore and Cheung 2015) and thus government-allocated risks may also influence other project risks such as the occurrence of delay in financial closure as a result of delays by government departments in issuing relevant approvals or permits. Thus, this research further validates the findings and PPP risks reported in previous studies.

The research reported in this paper has delivered on several objectives. First, it established a 45 factor risk list and identified 22 critical risks, based on input from a wide array of PPP stakeholders from a developing country perspective, in two of the most active infrastructure sectors for private investment, i.e., power and transport sectors. This also addresses the paucity of research studies in the extant literature that explores pertinent risks for multiple infrastructure sectors to provide critical insights on how risks and their significance vary across sectors. The results indicate that the most critical risks in the power sector are delay in financial closure, delay in project approvals and permits, payment risk, and financing risk, whereas the highest impact risks in the transport infrastructure sector include land acquisition, financing risk, unfavorable national/international economy, delay in financial closure, and construction risk. The critical risks were further categorized in seven CRGs which provide better understanding of the main issues that require immediate stakeholders' attention. Second, this research presents a novel methodology to analyze project risks and obtain assessments of risk level of CRGs and overall sector and project by employing fuzzy measure and the Choquet fuzzy integral which can accommodate interactions among risk factors. This research also adopts FST to model human subjective judgment in risk assessment. The results of model application indicate *public sector maturity* as the most critical risk group for power infrastructure projects, whereas the *project planning and implementation* risk group is determined to be the most significant for transport infrastructure projects with both the sectors determined as *moderately* risky. In addition to sectoral risk evaluation, the methodology was also extended to perform a case-study analysis to analyze summary level risk indicators at the CRG and project level and to demonstrate its applicability for project risk analysis. Validation results also show the robustness of the model for project risk assessment. The presented methodology has multiple practical implications in terms of enabling: identification of the most critical risk factors that warrant management attention and further detailed analysis (Ameyaw and Chan 2015b), identification of CRGs for efficient planning and execution of remedial actions, assessment of overall risk level of the project by the stakeholders (Xu et al. 2010), prioritization of projects based on risk level to decide projects worth promotion by the private sector (Zayed et al. 2008), and assessment of the local country conditions from a risk perspective before setting up the project structure and normal due diligence (Ameyaw and Chan 2015b). Therefore, this research was successful in contributing to existing PPP risk management literature by establishing critical risks for key infrastructure sectors and by demonstrating and validating a risk assessment model to allow assessment of the impact of these risks on stakeholders' value ambitions. Other contributions include comparative analysis of PPP sectoral risks and discussion on the underlying causal factors.

The presented methodology can be modified to suit the specific contextual needs by adjusting for critical risks, risk groups, and number of experts for soliciting inputs. In addition, this research suffers from some limitations that deserve to be mentioned here. The established risk register represents information from existing literature and inputs of local PPP experts. Although most of the risk factors would generally be applicable for any developing country context, certain country, sector, and project-specific situations might dictate otherwise. Hence, any generalizations need to be considered cautiously, specifically with regards to the criticality of risks. Also, there are several methodologies available to evaluate the fuzzy measure for Choquet fuzzy integral analysis. Other methods can be employed and compared with the applied methodology to determine which methods provide more practical and representative solutions. Furthermore, the results obtained by the application of the proposed methodology need to be validated with a larger set of project data and compared with other available methods in the existing literature to concretely establish relative advantages and disadvantages in the context of project risk assessment.

Data Availability Statement

Data generated or analyzed during the study are available from the corresponding author by request. Information about the *Journal*'s data-sharing policy can be found here: http://ascelibrary.org/doi/10.1061/(ASCE)CO.1943-7862.0001263.

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