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Towards a better modelling and assessment of construction risk: Insights from a literature review

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Abstract

This paper reviews the literature of construction risk modelling and assessment. It also reviews the real practice of risk assessment. The review resulted in significant results, summarised as follows. There has been a major shift in risk perception from an estimation variance into a project attribute. Although the Probability–Impact risk model is prevailing, substantial efforts are being put to improving it reflecting the increasing complexity of construction projects. The literature lacks a comprehensive assessment approach capable of capturing risk impact on different project objectives. Obtaining a realistic project risk level demands an effective mechanism for aggregating individual risk assessments. The various assessment tools suffer from low take-up; professionals typically rely on their experience. It is concluded that a simple analytical tool that uses risk cost as a common scale and utilises professional experience could be a viable option to facilitate closing the gap between theory and practice of risk assessment.

Keywords: Construction; Literature review; Project management; Risk assessment; Risk assessment practice; Risk cost; Risk modelling

1. Introduction

"No construction project is risk free. Risk can be managed, minimized, shared, transferred or accepted. It cannot be ignored" (Latham, 1994, p.14). The construction industry is often considered as a risky business due to its complexity and the strategic nature of its products. It involves numerous stakeholders, long production duration and an open production system, entailing significant interaction between internal and external environments (BSI-6079-4, 2006). Such organisational and technological complexity generates enormous risks (Zou et al., 2007). Unfortunately, the construction industry has a poor reputation in risk analysis when compared with other industries such as finance or insurance (Laryea, 2008). Although every step of a risk management process has received huge attention from researchers, it seems that risk assessment is a controversial issue (Baloi and Price, 2003). Traditionally the focus has been on quantitative risk assessment (Tah and Carr, 2001) despite the difficulties encountered in obtaining objective probabilities, and frequencies, in the construction industry. This difficulty stems from the fact that construction projects are very often one-off enterprises (Flanagan and Norman, 1993). This reality is a key driver behind the obligation of project managers being to rely on subjective probabilities as Winch (2003) concluded. In fact, risk in many cases is subjectively dealt with through adding an approximate contingency sum (Kangari and Riggs, 1989). Therefore, individual knowledge, experience, intuitive judgement and rules of thumb should be structured to facilitate risk assessment (Dikmen et al., 2007b).

Risk assessment is inherently related to risk modelling. The Probability–Impact (P–I) risk model is prevailing and risk is usually assessed through assessing its probability of occurrence and impact. However, the P–I risk model was subject to criticism from researchers who discussed potential improvements in it. Moreover, researchers have investigated different theories, tools

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and techniques for aiding risk assessment. Unfortunately, there is a clear gap between the theory and practice of risk modelling and assessment. Hence, it is of crucial importance to understand the actual practice of risk analysis and review the development of construction risk modelling and assessment in an attempt to research viable alternatives that may contribute to closing this gap. This paper presents the result of an extensive review of the published literature of construction project risk modelling and assessment in English. The research focused mainly on peer-reviewed articles published in academic journals specialised in construction management, project management, risk analysis, and management science. The following databases were utilised for researching relevant papers: Science Direct, Web of Science, ABI-Inform (Proquest), Business Source Premier (EBSCO), Emerald, and Sage Management & Organization Studies. To further support reviewing the published literature, the Google Scholar search engine was deployed. The following key words were used in the search: project risk, construction risk, risk analysis, risk assessment, risk modelling, and risk management. These words were used after discussing them with research colleagues. However, different combinations of them were used to validate the extensiveness of the search results. Moreover, other key words were tried to investigate any differences in the search results such as: risk model, risk modelling, uncertainty analysis, and project uncertainty. Besides computerised search, manual bibliographic search was also used. In many cases, reviewing the papers helped in identifying related papers. The review process took place between October 2008 and August 2009. However, regular search activities have been conducted since then to keep the review results updated. The search targeted all of the available articles in the databases in order to review the historical development of risk modelling and assessment. Hence, there was no time restriction when searching the databases. As a result, around 400 articles were reviewed. Eventually, 68 ones were considered as most relevant to the research aim and were subject to a detailed review. These papers, detailed in Appendix (A), cover the last three decades of project risk modelling and assessment history. To be included in the final list, papers had to meet the following criteria: 1) provide a methodology for assessing project risk; 2) use specific theory or technique for assessing risk; 3) present an attempt to improve project risk modelling; and 4) relate to construction or project management domain. In the next section of the paper, a chronological review of these 68 papers is provided. Later, the paper analyses and the results of the literature review will be discussed to enable eliciting the main themes and developmental trends. After that, a review of the actual practice of risk analysis is displayed in order to complement the review results and to enable defining the characteristics of practical alternatives. The paper ends with a summary of the key findings and conclusions.

2. Literature review

Risk analysis in construction industry is not new. It has its roots since the development of the Program Evaluation and Review Technique (PERT) in the 1950s for tackling uncertainty in project duration. Conventionally, risk has been dealt with as an estimation variance benefiting from the dominance of Probability Theory (PT). In the 1980s, however, risk began to be perceived as a project attribute and Risk Management (RM) became a well-established project management function. During the 1990s researchers investigated different theories to account for the special nature of construction risk, and after the beginning of the new millennium risk assessment flourished as a hot research topic.

2.1. Before the 1980s

Although the origins of risk analysis can be traced back to as far as 3200 BC (Baker et al., 1999b), risk had not appeared in construction literature until 1960s (Edwards and Bowen, 1998). Baker et al. (1999b) argued that the term “risk analysis” was used for the first time by Hertz (1964) who utilised the computer for generating probability distributions of investment projects rates of return. Reviewing literature reveals that risk analysis publications started in the USA where risk was considered implicitly when researching other problems like bidding and cost and duration estimation. Risk was modelled as an estimation variance and RM was perceived as a way of reaching more accurate estimates during the tendering stage. According to Edwards and Bowen (1998), statistical methods were initially used before employing Monte-Carlo Simulation (MCS) during the 1970s. Despite the dominance of the probabilistic methods and MCS, the dearth in risk analysis publication is very evident in that era; very few articles about risk analysis can be referred to like Carr (1977), Friedman (1956), Gates (1960, 1967, 1971), Gates and Scarpa (1974), Morin and Clough (1969), and Spooner (1974). Regarding risk management, it was the end of the 1970s when project RM started to became an essential component of project management (Merna and Al-Thani, 2008). Actually, reviewing the literature reveals that the beginning of the 1980s is the actual start of perceiving RM as an independent project management function and research domain.

2.2. The 1980s

In the 1980s PT-based tools and MCS continued to dominate risk assessment. However, Fuzzy Sets Theory (FST) was introduced at the end of this decade as a viable alternative for tackling subjectivity in construction risk assessment. Chapman and Cooper (1983) presented one of the earliest attempts to structure project risks and, systematically, identify their sources. They introduced the “risk engineering” approach, which integrated different tools and techniques like PERT and decision trees, for combining risk events and producing probability distributions of activities and project durations. Hence, risk was modelled as a distribution variance of an activity or project duration. Diekmann (1983), however, modelled risk as a variation of cost estimation. He reviewed different tools used for producing a probabilistic estimate of project cost and used MCS for such a purpose. Contrary to the previous two papers, Barnes (1983) modelled risk as probability and impact (P–I) with risk impact defined as a variance in cost estimate. In a subsequent paper, Cooper et al. (1985) presented a method for assessing project cost risk. A hierarchical risk breakdown structure was developed with project cost risk at the top of the hierarchy. Risk was modelled again as a variation of cost estimate. Beeston (1986) also modelled risk as an estimation variance and used MCS to generate more accurate estimates. Clark and Chapman (1987) also dealt with risk as an estimation variance while discussing the risk analysis methodology developed by the Projects Department of BP's Group Engineering and Technical Centre.

In one of the very few papers that highlighted the need for considering the impact of risk on specific project objectives, Franke (1987) advocated assessing risk impact financially. He proposed the use of "risk cost" as a common scale and adopted the P–I risk model. Here, risk cost is recommended, for the first time, to be used for measuring the different types of risk impact on project success factors. Such an approach provides a detailed and comprehensive risk impact assessment. Moreover, it is a practical way of quantifying risk impact and an easy approach for including risk impact in project cost estimation. Although this paper proposes a pioneering approach for assessing risk impact, the overall project risk level is treated in a rather simplistic manner. Project risk level is obtained through summing up the individual risk costs ignoring any interdependencies between these risks. Such an aggregation process may result in an unrealistic project risk. In the late 1980s, Kangari and Riggs (1989) discussed the potential usage of FST for risk assessment. It is the earliest paper that recommends FST for handling the subjectivity of construction risk assessment. Indeed, it is a very important paper and one of most cited. It presents an objective evaluation of the merits and shortcomings of FST for assessing construction risk. The concept of FST was developed by Lotfi Zadeh in 1965 to represent the uncertainty, using natural words, which the lack of precise crisp numbers can cause. FST represents uncertainty through linguistic variables and membership functions. Every linguistic variable is represented by a fuzzy set, a set of numbers, associated with a membership function. The membership function is a set of numbers between 0 and 1 representing the degrees of membership with 1 standing for complete belonging and 0 standing for complete non-belonging. Hence, the partial belonging to a set is the key difference between FST and the crisp set theory which is based on complete belonging or complete non-belonging to a set (Liu et al., 2002). As will be illustrated in the next sections, FST has flourished over the last two decades in assessing construction risk.

2.3. The 1990s

During the 1990s construction risk modelling and assessment gained momentum and became a hot research topic. Researchers primarily used two theories: PT and FST. Yet, in particular, they were keen to research other tools and techniques like the Analytical Hierarchy Process (AHP). Hull (1990) introduced different models, based on MCS and PERT, to assess proposal risks from cost and duration perspectives, while Yeo (1990) presented a "contingency engineering" method, using both a range estimate method and PERT, to assess project cost risk and to estimate contingency sums. It is one of the earliest attempts to estimate risk contingency in a systematic manner. Al Bahar and Crandall (1990), in turn, used influence diagramming and MCS to assess risk. They adopted the P–I risk model and provided a systematic approach for identifying, assessing and managing construction risks.

Pioneering its application in construction, Mustafa and Al-Bahar (1991) adopted the AHP to assess construction project risk. Becoming one of the most cited papers in the literature; it applied the concept of value and weight of AHP to assess risk probability and impact. It is evident from reviewing the literature that AHP has received a paramount attention from many researches. AHP was developed by Thomas Saaty and presented in Saaty (1980). It has received worldwide recognition as a powerful Multi Criteria Decision Making (MCDM) tool. It is a very useful tool for structuring complex decision making systematically. One of the core attributes of AHP is its ability to facilitate the decision maker's personal judgement in quantifying relative priorities of decision alternatives on a ratio scale. There is no doubt that AHP provided a vital approach for structuring the increasing complexity of construction projects and construction risk assessment. In fact, Mustafa and Al-Bahar (1991) presented a very good evaluation of the merits and limitations of AHP and its suitability for assessing construction risk.

Influence diagramming appeared again in Diekmann (1992) representing risky situations and MCS and FST were deployed to do risk assessment calculations. Similarly, Huseby and Skogen (1992) used influence diagramming and MCS to account for dependencies between risks and then assess them. They devised software called DynRisk to facilitate using influence diagramming and MCS. In one of the few attempts to price risk systematically, Paek et al. (1993) used FST to assist contractors in deciding on bid prices. Likewise, Tah et al. (1993) used FST to assist contractors in estimating risk contingency; the P–I risk model was adopted. AHP appeared again in Dey et al. (1994) in a risk assessment methodology which combined objective and subjective assessments; the P–I risk model was again adopted. Riggs et al. (1994) proposed an approach for quantifying and integrating technical, cost, and schedule risks through utility functions. AHP was used to elicit the utility functions and utility was used as a common scale for assessing the attractiveness of different scenarios. Actually, the proposed model could not assess risk; it could only assess the utilities of different risky scenarios. Williams (1995) conducted an extensive literature review of the available tools and methodologies of construction RM. He found that risk assessment used to focus on cost and duration related risks; quality related risks were neglected. He reported the lack of research towards assessing risk impact on different project objectives simultaneously and attributed that to the lack of a common assessment scale. Like Franke (1987), he recommended risk cost as a feasible solution. AHP was used again by Zhi (1995) to assess the risk levels of overseas construction projects; the P–I model was adopted and AHP was deployed with minor modification; the impact assessments fell in a [0–1] range instead of the AHP's formal 1–9 ordinal scale.

The limitations of the P–I risk model were discussed in Williams (1996). He argued that multiplying probability and impact produced an expected value of risk which is misleading and cannot be simply used to prioritise project risks. As a result, he suggested considering both probability and impact for prioritising risks. He also concluded that a three dimensional risk model: Probability–Impact–Predictability, recommended by Charette (1989), was a viable alternative to the P–I model. Similarly, Ward (1999) discussed the limitations of the P–I model and urged for improving risk assessment. He insisted that the multiple impacts of risk on specific project objectives should be considered before calculating the overall risk impact. Besides, he criticised the method of generating project risk level through summing up the numerical scores of separate Probability–Impact grids representing the assessments of project risks. As an alternative, he proposed using a weighted sum of alphabetical ratings. Although the alphabetical rating may be a feasible alternative, this approach may not be easily applicable for assessing project risk level. For instance, a risk rating could be expressed, based on its impacts on three project objectives, as 3A + 2C + 5D. Such a rating is very difficult to use when aggregating a large number of risk assessments with different scores on various project objectives.

Wirba et al. (1996) used FST to assess risk likelihood of occurrence using linguistic variables. In this paper, risk impact was considered as the cost of a risk response strategy. While this paper is widely cited, there is a concern about using the fuzzy weighted mean method aggregating risk assessments; this is a key point of weakness in FST as it only calculates the weighted average of the individual assessments. Although FST became more common, PT-based methods continued to be used. Dawood (1998) used MCS to estimate an activity or project duration with risk modelled as an estimation variance. Mulholland and Christian (1999), however, used PERT to estimate a project duration. Again, the variance of project duration represented project schedule risk; the larger the variance, the greater the risk associated with project duration.

2.4. The new millennium

Since 2000, attempts at better modelling and assessment of construction risk have intensified and tools have become more sophisticated benefiting from the availability of high capacity PCs. As a result, risk assessment, very often, was facilitated by decision support systems (DSSs). Despite their limitations, AHP and FST became the principal approaches for handling ill-defined and complex problems with subjectivity involved. Yet, PT-based techniques continued to appear in literature, but with less frequency if compared to the previous eras.

Chapman and Ward (2000) criticised the use of Probability–Impact grid to size risk arguing that it generated unnecessary uncertainty by over-simplifying the estimates of risk probability and impact. As an alternative, they proposed the 'minimalist' approach which identifies risks and assesses their probabilities and impacts by specifying ranges instead of single scores. Hastak and Shaked (2000) deployed AHP for assessing risks in international construction projects and adopted the P–I risk model. Although the developed method provided an assessment of project risk level, the assessment methodology was over-simplistic. Risks were subjectively assessed using a predetermined scale of 0–100, where 0 implies no risk and 100 implies maximum risk and project risk level was defined as the weighted sum of the individual assessments. Tah and Carr (2000) assessed risk probability and impact and risk interdependencies using FST. They tried to overcome the limitation of the fuzzy averaging rule by introducing a new aggregation formula based on the maximum risk estimate, *Emax*, using a modification factor (ξ) as follows: $E = \xi * Emax$. Although this aggregation rule is a vital alternative to the averaging one, it might not be an appropriate choice for every case. For instance, one may struggle in using it in the case of having more than one predominant risk factor. In fact, the researchers agreed that their method needed further investigation.

The methodology of the Department of Contract and Management Services in Western Australia used for ranking projects based on their risk levels was adopted by Baccarini and Archer (2001) for assessing risk. The methodology utilises the P–I risk model and calculates a risk score for each of project cost, time or quality. Although the methodology considers risk impact on specific project objectives, the aggregation rule is questionable. The scores of risk likelihood of occurrence and impacts on project cost, time and quality are averaged and then multiplied for generating individual risk scores. Eventually, project risk level is defined as the highest of the risk scores. Such an aggregation rule is over-simplistic and may not yield realistic assessments. Ben-David and Raz (2001) presented a model that optimises risk reduction actions through generating the most cost-effective combination of risk reduction actions. The P–I risk model was adopted and the impact was measured in monetary terms. The model allows including the impact of positive risk impacts such as potential savings or additional profit. Hence, the expected risk impact, positive or negative, is the product of the risk probability and impact. Although the model provides a practical method for gauging project risks, the overall project risk level, or the *total project risk exposure*, is over-simplistic. It is defined as the sum of the expected risk impacts which implies an assumption of risk independence which generates unrealistic project risk level.

Dey (2001) proposed a DSS for managing risk in the early stages of a construction project using AHP and decision trees. The tool aims to identify the best strategy for managing construction project risk through the expected monetary value (EMV) of every risk response strategy. The approach, hence, does not quantify the impact of any risk; it recommends the risk response scenario which has the lowest expected cost. In this paper, risk impact was represented by the extra cost and the extra time which was calculated to monetary equivalent. The DSS considered risk impact on project cost and duration only; it did not consider risk impact on the other project objectives. Moreover, it did not suggest a specific way of aggregating the various risk impacts. The PT-based tools appeared again; Xu and Tiong (2001) used stochastic programming as a tool for reaching accurate pricing. As in similar cases, risk was modelled as a variation in cost estimation. Tah and Carr (2001) utilised the FST for assessing risk and providing project risk rating. Although they calculated separate ratings of risk impact on project duration, cost, quality and safety, they did not propose a methodology for combining these separate ratings. Patterson and Neailey (2002), in turn, used linguistic variables for assessing risk probability and impact. However, they proposed calculating project risk level through averaging the individual risk assessments.

It seems that researchers have tried every possible theory and technique for assessing risk. Moreover, aggregating individual risks was always a key task; researchers tried different approaches for generating a representative project risk level. Baloi and Price (2003) presented a very important review of the available tools and methodologies for risk assessment. They concluded that FST was a key alternative to suit the case of the construction industry.

The nature of risk and the meaning of the term "risk" was a matter of concern for the researchers. Ward and Chapman (2003) proposed using the term *project uncertainty management* instead of *project risk management*. They argued that the term risk was conveying a message of threat whereas the word uncertainty was more suitable for saying that there was opportunity as well. A different meaning of the term risk was used by Jannadi and Almishari (2003). They defined risk as the potential damage that may affect personnel or property. Hence, risk was specifically used to stand for health and safety problems. Jannadi and Almishari (2003) proposed a three dimensional risk model containing risk probability of occurrence, severity of impact and 'exposure' to hazards. They also devised software called Risk Assessor Model (RAM) to generate risk scores. However, they did not propose a specific methodology for aggregating risk ratings. The different natures of risk were also addressed by Choi et al. (2004) who deployed FST for analysing risk in the underground construction projects. They devised an integrated DSS capable of handling different types of uncertainty, using both frequencies and subjective judgements, based on the available amount of information.

2.5. Post 2005

The sharp increase in the number of risk assessment and modelling papers published after 2005 is remarkable. Moreover, an evident trend for improving risk modelling can be detected. The majority of the published papers dealt with risk as a project attribute rather than an estimation variance. Such a major shift in risk perception has resulted, in many cases, in integrating risk assessment in comprehensive decision making frameworks. The increasing complexity of risk assessment was manifested in the proposed development in risk modelling and the extensive deployment of sophisticated DSSs.

Shang et al. (2005) used FST to assess risk probability and impact and developed a DSS for aiding construction risk assessment in the design stage. The DSS allows different project members to access via the WWW and to express their assessments. These assessments are then weighted and synthesised. A new risk model was introduced by Cervone (2006) to consider the interdependencies between project risks. It was argued that the P–I risk model suffers from the assumption that risks are independent from their environment, which is not the case in a project context. The proposed model included an additional dimension called "risk discrimination" using the definition of Kendrick (2003). According to Cervone (2006, p.260) risk discrimination "*is designed to gauge the impact of a risk on the overall framework of the project*, *rather than looking at each risk as an independent variable within the project*". In the proposed model, risk is modelled as follows: $R = (P * I) / D$. The new risk model appreciates the interdependencies between risks through reducing their independent scores $P * I$. The reduction is performed through dividing the independent $P * I$ score by the risk discrimination factor D. In fact, the same model was adopted by Nieto-Morote and Ruz-Vila (2011) as will be illustrated later. Risk interdependency issue was also addressed by Poh and Tah (2006). They used influence networks to capture interdependencies among the factors affecting the duration and cost of a construction activity. However, they did not suggest a tool for assessing cost and duration risk. In a different attempt to model the interdependencies between project risks, Thomas et al. (2006) used fault tree to model different scenarios and utilised linguistic variables to assess risk probability and impact. They attempted to improve risk assessments by considering the opinions of different experts; they called this method Fuzzy-Delphi. The proposed model does not assess project risk; instead it provides a tool for assessing the risk levels of specific risk scenarios.

Dikmen and Birgonul (2006) used AHP within a MCDM framework for assessing risk and opportunity in international construction projects. The P–I risk model was adopted and the overall risk level of a project was calculated by summing up the individual risk assessments. Truly, the rather simplistic approach of generating project risk level is questionable. Moreover, the model cannot be used in a straightforward way to quantify or assess project risk; it compares the risks of one project with their counterparts in other projects and provides relative risk scores. In fact, the relative nature of the results generated by AHP-based models is one of the key limitations of using AHP for risk assessment. AHP was also used, in combination with Utility Theory, by Hsueh et al. (2007) to develop a multi-criteria risk assessment model for construction joint-ventures. The model did not provide a project risk assessment; it calculated the expected utility of the project in question. Hence, the higher the expected utility value, the lower the project risk level.

In order to improve risk modelling, Aven et al. (2007) discussed the nature of risk and argued that some risks are more manageable than others. This means that the chance of reducing the downside effect of one risk may be larger than other risks. To reflect this idea, the concept of risk "manageability" was introduced. According to Aven et al. (2007), an alternative with medium risk level and low manageability could eventually be riskier than an option with high risk and high manageability. Although manageability is a key issue to be considered when assessing risk, Aven et al. (2007) did not suggest a specific methodology for assessing it. Similarly, Dikmen et al. (2007b) addressed the issue of risk *manageability* or "controllability", but in a rather different manner. They argued that the capability of a company in managing project risks should be considered when assessing them. As a result, they consider the experience of a construction firm as an influencing factor that mitigates project risk level. Actually, Dikmen et al. (2007b) dealt with

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manageability as an attribute of the company rather than an integrated attribute of risk itself. This is a different interpretation from the manageability concept of Aven et al. (2007). In another proposal to improve modelling risk, Cagno et al. (2007) discussed risk "controllability" again but from a different perspective. They adopted the P–I risk model and defined risk 'controllability' as the ratio between the expected risk impact, and monetary equivalent, before and after applying mitigating actions. In other words, risk controllability is dealt with as a tool for justifying mitigating actions economically. The proposed model was aimed to be used at a company level; at a project level risk is dealt with as a variation in project parameters. The P–I risk model was again subject to another improvement by Zeng et al. (2007) through adding a third dimension; "Factor Index" (FI). This dimension reflects the surrounding environment and the influences between the identified risks. In other words, it is representing the complexity of risk assessment within a real project context. Risk is modelled as: $R = L * S * FI$ where L stands for likelihood of occurrence and S stands for severity of risk impact. The complexity of risk assessment was also addressed by Ackermann et al. (2007). According to them, the interaction project risks can cause the most damage to a project. Hence, they suggested looking at project risks as a network of interrelated possible events, which they referred to as 'risk systemicity'. They argued that due to their interactions, project risks can form a portfolio with an overall impact greater than the sum of the individual risk impacts. Besides, they explained that one risk occurrence may result in reinforcement of the likelihood of other risks occurring. Hence, they urged for considering this "complex chain of outcomes" when assessing risks as well as the risks themselves. Indeed, such a holistic appreciation of the complexity of risk assessment is crucial for obtaining realistic results.

Zeng et al. (2007) used FST to handle subjectivity in construction risk assessment and deployed AHP to prioritise risks and derive relative weights for them. Similarly, Zhang and Zou (2007) combined the strengths of FST and AHP within, what they call, a "Fuzzy–AHP" approach for assessing risks in joint venture construction projects in China. It is worth noting that both AHP and FST have limitations and utilising them together does not necessarily overcome their limitations. Like Zeng et al. (2007), Zhang (2007) insisted that assessing risk should not neglect the surrounding environment. He argued that project environment has a mitigating effect on risk assessment which is largely neglected when using statistical methods. He advocated considering the specific nature of a project when assessing risk and proposed the concept of "project vulnerability". Project vulnerability has two distinct dimensions: the exposure of a project to a risk; and the capacity of a project system to cope with risk impacts. It is a very important paper trying to push research towards a more realistic risk assessment. However, it did not suggest a method for assessing vulnerability or incorporating in risk assessment or risk model. Yet, it was a basis for an innovative approach for handling project risks suggested by Vidal and Marle (2012) as will be discussed later. While estimating construction project mark-up through Case-Based Reasoning, Dikmen et al. (2007a) considered risk a project attribute which can be handled through calculating an accurate contingency sum. In another paper Dikmen et al. (2007c) used the Analytic Network Process (ANP) for project appraisal and also addressed risk as a major project attribute. Zou et al. (2007) investigated the key risks affecting construction industry in China. Risks were identified and prioritised according to their significance which is the impact on project objectives such as cost, time, quality, safety and environmental sustainability. In this study, the P–I risk model was adopted and project risk level was defined as the average of the assessed risks. Risk significance, however, was defined differently in Han et al. (2008). A three dimensional risk model, *Significance–Probability–Impact*, was proposed with "risk significance" and defined as the degree to which a practical expert feels risk intuitively. This includes a general recognition of risk, the difficulty of gaining information and implementing management skills, the degree of indirect or potential loss and the relationship between project profitability and the analyst's attitude toward risk. Although the paper presents a DSS for assessing the risk level of specific risk path, source-event, or project scenario, it does not suggest any mechanism for aggregating individual risk assessments or generating project risk level. Zayed et al. (2008), though, proposed a risk model that calculates project risk level for prioritising a set of projects. Project risk level was defined as the product of two risk indices: $R1$ that measures the risks on a macro level of the project and $R2$ that measures the micro level ones. Hence, project risk is modelled as: $R = R1 * R2$. Both $R1$ and $R2$ are defined as weighted sums of risk effects assessed by individual experts, with AHP deployed to generate importance weights of the risks. In this paper the P–I risk model was not adopted. Instead, a collective score, risk effect Ei, is used. Obviously, the method of generating project risk level neglects the interdependencies between risks.

Despite the dominance of the analytical approaches that utilise FST and AHP, the stochastic methods continued to appear in the literature. Cioffi and Khamooshi (2009) presented a statistical methodology for combining risk impacts and generating an overall impact, at a given confidence level, which lead to an appropriate contingency budget. The paper adopted the P–I risk model and defined risk impact as the incurred cost of risk occurrence. This methodology had a weakness in requiring the probabilities of occurrence to be averaged in order to perform the aggregation at certain confidence levels. In fact, another stochastic method, the MCS-based methodology developed by the Washington State Department of Transportation (WSDOT) for estimating project cost, was presented by Molenaar (2005). This methodology adopts the P–I risk model and measure risk impact by the extra cost incurred because of a risk happening. Similar to the previous two papers, Luu et al. (2009) did not deal with risk as a project attribute; they modelled risk as the probability of construction project delay. Moreover, they used Bayesian Belief Network (BBN) to model the relationships between the risks that cause project delay and to quantify the probability of a construction project delay. Fung et al. (2010) developed an Excel-based tool to assess project risk level from a safety perspective. Risk was modelled as a multiplication of an accident frequency and its severity. Severity, or risk impact, was defined as the sum of three risk impacts: extra time, extra cost and personal injury. The researchers adopted the methodology of unifying different types of risk impact proposed by Larsson and Field (2002). The three types of impact were normalised into scores between 0–1. Hence, the maximum possible severity of a risk is 3. Although the tool was able to rank the risks according to their scores, aggregating risk scores for generating project risk level was not considered. Mojtahedi et al. (2010), in turn, tried to extend the conventional project risk assessment by including health and safety and environmental aspects. They applied the multiple attribute group decision making technique (GTOPSIS) for collating different opinions of risk experts to prioritise risks. They also considered risk impact on project cost, duration and health, safety and environment. The complexity and subjectivity of construction risk assessment was handled by Nieto-Morote and Ruz-Vila (2011) through combining the strength of AHP and FST. Although such a combination was suggested previously, Zeng et al. (2007) and Zhang and Zou (2007) for instance, the researchers tried to improve risk modelling and assessment via adopting the risk model of Cervone (2006) which was discussed earlier in the paper. They used linguistic terms to assess risk likelihood, impact and discrimination. They also used the fuzzy arithmetic average to aggregate the assessments of different experts and the fuzzy multiplication rule to generate a project risk level. The FST appeared again in Lazzerini and Mkrtchyan (2011) for tackling the subjectivity and complexity of risk assessment, due to the interdependencies and causalities between risks, through using the Extended Fuzzy Cognitive Maps (E-FCMs). They also used the Fuzzy Cognitive Maps for synthesising the opinions of different experts and supporting group decision making and risk assessment. The complexity of risk management was also discussed in Marle and Vidal (2011) who argued that the existing techniques have a limitation in considering the interactions between risks when assessing them. They stated that the existing tools generally deal with interdependent risks as if they were independent. Hence, the researchers dealt with project risks from a project complexity-based perspective and focused on capturing the interactions between risks that affect the various elements of the project. In fact, project complexity has received enormous attention over the last two decades. Researchers have investigated the concept of project complexity and the link between complexity and risk. Very often, risk was considered as an element of project complexity or as a result of it. Actually, the ongoing problem of lacking enough information is a major cause of the complexity of project risks assessment. Hashemi et al. (2011) investigated the problem of lacking enough data to use the parametric statistical tools for estimating risk probability and impact. They suggested using a nonparametric technique: Bootstrap technique, to generate interval values with smaller standard deviations. Fang and Marle (2012), however, tackled the complexity issue in a different manner. They represented the complex interactions between risks through networks and used the design structure matrix (DSM) for modelling the casual relationships between the risks. They also used the AHP for evaluating risk interactions. Simulation technique is used to analyse the risk propagation phenomena in the network and to re-evaluate risk probabilities and impacts in different scenarios. Moreover, the complexity of the assessment task was handled through an integrated DSS that enables decision makers to conduct a comprehensive risk management, identification, analysis and control, effectively and efficiently.

Finally, risk assessment was handled in a rather innovative manner by Vidal and Marle (2012). They utilised the concept of project vulnerability of Zhang (2007) and the Systems Theory and argued that analysing project risks could be better conducted through focusing on the existing weaknesses of the project systems. Hence, instead of assessing risks directly, vulnerability management enables assessing the weaknesses of the systems responsible for managing project risks. Vulnerability management was recommended as a promising tool for handling the complexity of the projects and project risk analysis. Indeed this is a rather innovative way of looking at project risks; it may open doors for new ways of analysing project risks and evaluating project performance.

To the researcher's knowledge, the above literature review reflects the main development trends in project risk modelling and assessment over the last five decades. The next section of the paper provides a thorough analysis and discussion of the findings of this review.

3. Analysis and discussion of risk modelling and assessment literature

3.1. Risk modelling

Reviewing the literature shows that construction risk has traditionally been perceived as the variance of cost or duration estimation. Gradually, there has been a shift in perception towards seeing it as a project attribute. As a project attribute, risk is mainly modelled as a multiplication of probability of occurrence and Impact. It is evident that the P–I risk model dominates the literature. However, a considerable number of improvement proposals can be appreciated. These improvement proposals can be summarised by:

- Predictability: Charette (1989) proposed adding 'predictability' as a third dimension to the P–I risk model. This improvement was braised by Williams (1996).
- Exposure: Jannadi and Almishari (2003) added the extent of exposure to risk as a third dimension to the P–I model;
- Discrimination: Cervone (2006) called on considering the interdependencies between risks through reducing their independent scores generated by the P–I model;
- Manageability: Aven et al. (2007) argued that some risks are more manageable than others and urged analysts to consider this fact when assessing risks. Incorporating risk manageability was also suggested by Dikmen et al. (2007b), but as an influencing factor that could mitigate the overall project risk level;
- Controllability: Cagno et al. (2007) considered 'risk controllability' as a ratio between the expected risk impacts before and after applying specific mitigation actions;
- Factor Index: Zeng et al. (2007) addressed the influence of the surrounding environment and the interdependencies between the identified risks by incorporating the factor index (I) as a third dimension in the P–I risk model;

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- Project Vulnerability: Zhang (2007) advocated extending project risk analysis process by incorporating project vulnerability in order not to neglect the mediating effect of project environment on risk impact. Project vulnerability was innovatively deployed by Vidal and Marle (2012) who argued that analysing project risks could be better conducted through focusing on the existing weaknesses. They introduced vulnerability management which enables assessing the weaknesses of the systems responsible for managing project risks;
- Significance: Han et al. (2008) added 'risk significance' as a third dimension to the P–I model in order to reflect the unique nature of risk and the intuition of risk analysts when assessing a risk.

The above development proposals have suggested different approaches. Aven et al. (2007) and Zhang (2007) called on considering risk manageability and project vulnerability when assessing risk without recommending a specific method to do that. Vidal and Marle (2012) suggested focusing on project weaknesses for managing its risks. Jannadi and Almishari (2003), Cervone (2006), Zeng et al. (2007), and Han et al. (2008), however, extended the P–I model and incorporated additional dimensions. Dikmen et al. (2007b), though, incorporated risk manageability as an influencing factor on project risk level. Whatever the format of the improvement was, the aim was to reflect the complexity of risk assessment and to make the P–I model more reflective through incorporating the unique nature of the risk and appreciating the influence of the surrounding environment and the interdependencies between risks.

Among these different approaches, the notion of extending the P–I risk model by incorporating additional explicit parameter(s) seems practical and convenient. For instance, the proposed incorporation of "risk manageability" by Dikmen et al. (2007b) as an influencing factor on project risk level might not be very helpful. It would be difficult for a decision maker to provide an accurate figure that reflects his or her experience, or the company's experience, in controlling project risks collectively; it may be much easier for the analyst to assess his or her experience in managing individual risks. Thus, when aggregating individual risk assessments, the manageability of project risks will be effectively established and incorporated. The author advocates the idea of extending the P–I risk model to incorporate additional parameters capable of reflecting the true nature of the risk and the experience of the management team in handling risk, the complexity of project systems that may affect risk assessment and the interaction between project risks. Such an extension would provide the basis for a detailed and realistic risk assessment. Moreover, such a model, that incorporates the influencing factors on risk assessment, comes into alignment with the complexity-driven approaches increasingly used for assessing project risk. Hence, the additional parameters should clearly reflect:

- The unique nature of a risk and the experience of the risk management team in controlling its impact and mitigating it;
- The interdependencies between the identified risks; and
- The effect of the surrounding project environment on risk probability and impact.

The additional parameters will function as mitigation coefficients with proportional values between 0 and 1. They are responsible for reducing the maximum risk assessment, generated by the P–I model, after taking the above points into considerations. Hence, the parameters require very clear definitions associated with specific value ranges.

3.2. Construction risk assessment

When examining the published literature of project risk assessment, two levels of analysis can be recognised: risk assessment and project risk level estimation.

3.2.1. Risk assessment

Different approaches have been adopted for assessing project risks. At first, researchers used statistical methods based on PT for dealing with duration risk or cost risk. This approach perceived risk as an estimation variance. In alignment with this perception, objective probability, or frequency, has been always sought after. Gradually, many researchers concluded that human factors, intuition, professional experience and personal judgement were essential for risk assessment. To reflect this conclusion, FST was introduced as a viable alternative for handling subjectivity in construction risk assessment. Besides the subjectivity issue, researchers were faced by the ever increasing complexity in risk assessment due to the growing complexity in construction projects (Tah and Carr, 2000). To deal with this challenge, AHP was perceived as an effective tool for handling the complexity in construction risk assessment. It has provided a systematic approach to structuring risk assessment problems by providing a logical approach for assessing risk impacts and allocating importance weighting. In fact, the complexity surrounding risk assessment has attracted huge attention. Researchers have tried various approaches for representing the interdependencies between project risks and reflecting the complexity of the surrounding environment (Ackermann et al., 2007; Baloi and Price, 2003; Cagno et al., 2007; Choi et al., 2004; Diekmann, 1992; Han et al., 2008; Hastak and Shaked, 2000; Kangari and Riggs, 1989; Lazzerini and Mkrtchyan, 2011; Mustafa and Al-Bahar, 1991; Nieto-Morote and Ruz-Vila, 2011; Thomas et al., 2006; Zeng et al., 2007; Zhang and Zou, 2007). Yet, AHP has enjoyed popularity recently. The wide adoption of AHP over the last two decades reflected the change in risk perception from an estimation variance into a project attribute. In fact, Laryea and Hughes (2008) referred to a paradigm shift in risk assessment from "classicalism"; using PT-based and simulation tools, towards "conceptualism"; using analytical tools. It is clear that the change in risk perception was coupled with a change in the tools for assessing risks. According to Laryea and Hughes (2008), however, the paradigm shift did not result in a greater adoption of the analytical tools by professionals. They argued that the take-up of the available risk assessment tools by practitioners is quite limited. The limited adoption of risk assessment tools does not hamper their potential. Research findings tell us that people who use advanced risk assessment methods appreciate their potential and feel positive about their benefits (Simister, 1994). Indeed, the existing gap between theory and practice should galvanise the efforts towards investigating more suitable theories and approaches that appeal to practitioners and reflect their experience and practice. Moreover, simplicity is a key factor for encouraging professionals to use risk assessment tools as will be discussed later in the paper. Furthermore, risk assessment must be facilitated by a user friendly DSS that structures the complexity of the task and allows professionals to implement their strategies and tactics in a rather easy and transparent manner.

In terms of risk impact assessment, it is striking how neglected the analysis of project quality risk is; the attention is still focused on cost risk or duration cost. In fact, literature lacks sufficient research on assessing risk impact on project quality or other strategic objectives. Subsequently, it lacks an assessment methodology that is capable of understanding risk impact on all project success objectives. The reason for such scarcity is attributed to the lack of a common scale (Williams, 1995). Yet, the most convenient common scale is thought to be the risk cost (Franke, 1987; Williams, 1995). Actually, risk cost has been used as a risk impact measurement scale by different researchers (Ben-David and Raz, 2001; Cagno et al., 2007; Cioffi and Khamooshi, 2009; Fan and Yu, 2004; Franke, 1987; Molenaar, 2005). Nevertheless, none of them used risk cost for assessing risk impact on different project objectives. In the cases using monetary equivalents for quantifying risk impact, the assessment outcome is an expected contingency sum to cover the risk or an expected cost of mitigating its impact. Hence, it is worth investigating an assessment methodology that enables assessing risk impact of specific project objectives using risk cost as a common scale. This could successfully lead to a comprehensive risk assessment and a realistic assessment of project risk level. Although one may question the suitability of using risk cost as a scale for assessing intangible element like quality risk for instance, the author believes that it could be a practical approach. Practitioners who price residual risks, the unknown unknowns, and provide a contingency allowance for covering them should be able to price the impact of the known unknowns, the risks, on project quality. Quantifying risk, pricing it, might be more appealing for practitioners due to the fact that the vast majority of the existing risk assessment tools provide a risk rating, numerical scores or linguistic variables, rather than an actual quantification. Truly, this might to some extent explain the low take-up of these tools. Hence, using risk cost as a measurement scale may contribute to closing the gap between theory and practice.

3.2.2. Project risk level

Different approaches were utilised to obtain a project risk level. Conventionally, researchers used PT-based techniques, PERT and MCS mainly, for combining the probability distributions of the activities' durations or costs and assessing the risk of project cost overrun or project delay. As mentioned earlier, the perception of project risk has gradually changed from an estimation variance into a project attribute. At first, risk was dealt with as a project attribute that can be analysed at a project level. Such an approach is sufficient for analysing the risk of small projects, not large complex ones (Dey et al., 1994). Increasingly, systematic and more sophisticated approaches have been adopted to handle risks in the increasingly complex projects. Project risks are systematically identified, categorised and structured in different manners such as influence diagrams, Bayesian networks, fault trees and the hierarchical risk breakdown structure which is believed to be the most commonly used one. The sophistication of the risk structures reflected the complexity of the project systems and the interdependencies between the risks. Aggregating the individual risk assessments across their structures for generating an estimate of the project risk level was a challenge. In most of the cases the aggregation mechanism has averaged the individual risk assessments. The fuzzy averaging rule for instance has been used widely for aggregating the individual risk assessments in linguistic terms. Averaging might not be the best option for obtaining a realistic risk assessment. In other cases, project risk level was obtained as the weighted sum of the individual assessments. Such an approach has a limitation of assuming that the aggregated risks are independent. Utility Theory was also employed for estimating project risk level. Project utility represented the attractiveness or the risk level of a project; the smaller the project utility the bigger the risk level. In this case, the overall project utility was derived either by a simple or a weighted sum of individual utilities. Again, this approach has a limitation of being over-simplistic due to the assumption of independence between risk factors (Dikmen et al., 2004). One could argue that the key for obtaining a realistic project risk level is starting with realistic risk assessments and then deploying an effective aggregation mechanism that keeps the anatomy of the individual assessments. Therefore, researching a novel approach for assessing risks and utilising an effective aggregation rule is crucial for a successful project risk assessment. Besides, producing novel alternatives should be appealing for the end users. Hence, understanding the reasons of the low take-up of the existing tools is essential for devising better alternatives and closing the existing gap between the theory and practice of risk assessment.

4. Surveying the actual practice of risk assessment

While project management literature is rich in papers addressing risk management, few papers have researched the actual practice of risk assessment and investigated the practitioners' points of view regarding the available tools and DSSs. Nonetheless, the existing literature gives a good insight about these issues. Tah et al. (1994) researched the practice of cost estimation and the usage of statistical tools for assessing the risk of cost overburden in construction projects. They found that all contractors did not perform any form of statistical analysis of risk. Contractors explained such an attitude by indicating that statistical tools could not effectively represent the unique nature of construction risk. Akintoye and MacLeod (1997) investigated the actual practice of RM in the UK construction industry. They argued that experience and intuition were key tools for risk assessment. Moreover, they found that sophisticated quantitative tools were not widely used for assessing risk. Similar results were obtained by Shen (1997) who administered a survey of risk management practice in Hong Kong. The survey revealed that experience and subjective judgement were the most effective and widely used tools for managing risks. The results also showed a very limited usage of quantitative techniques due to limited understanding and lack of experience in such methods. Based on these studies and other similar ones like Potts and Weston (1996) and Jackson et al. (1997), Wood and Ellis (2003) investigated the actual practice of RM in the UK construction industry. Where the previous studies administered questionnaires to collect data, Wood and Ellis (2003) conducted in-depth interviews in an attempt to get deeper insights and generate qualitative results. Their research findings, to a large extent, confirmed many of the findings of the previous questionnaire-based research.

Baker et al. (1998) surveyed the most successful qualitative and quantitative risk analysis tools in construction and Oil and Gas industries. The researchers concluded that the most frequently used qualitative tools, and the most successful ones, are personal and corporate experience and engineering judgement. Regarding quantitative risk analysis, it was found that the Expected Monetary Value (EMV), break-even analysis, scenario analysis and sensitivity analysis were the most widely used. According to them, these tools are mainly used for handling financial risks. Moreover, they suggested that this may reflect the "preoccupation" of construction industry with finance. It is notable that these tools are not sophisticated in general. This may suggest that practitioners tend to use simple quantitative tools for supporting their experience and judgement when assessing construction risks. In fact, this suggestion was confirmed by Wood and Ellis (2003). According to Wood and Ellis (2003), reliance on personal judgement and experience is prevailing; RM is usually conducted using simple tools like checklists and risk registers; using complex analysis techniques is limited due to scepticism about their usefulness; cost is used as a measure for risk impact; and RM is believed to benefit particularly in project budgeting and contingency estimation. For comparison and confirmation reasons, Lyons and Skitmore (2004) conducted a survey among 200 construction contractors in Queensland in Australia. In general, the results were consistent with the results of the previous studies and the results of another three surveys in different times and countries (Baker et al., 1999a; Raz and Michael, 2001; Uher and Toakley, 1999). The results confirmed that intuition, judgement and experience are the most frequently used risk assessment techniques. Moreover, they showed that qualitative methods for risk assessment were used more frequently than quantitative or semi-qualitative methods. Similar results were presented by Dikmen et al. (2004) who found that personal judgement and experience were the key tools for assessing risk qualitatively. They also found that sensitivity analysis and decision tree were the most commonly used tools for quantitative assessment. In another study, Warszawski and Sacks (2004) argued that sensitivity analysis was the most commonly used tool for risk assessment in construction. They explained their results by arguing that the more sophisticated methods were not widely used because they required detailed input information which might not be available in every case.

The common theme emerging from the above studies shows that the actual practice of risk assessment is, very much, based on experience and personal judgement. Besides, practitioners do not use the available tools or DSSs extensively; they prefer to conduct risk analysis in a rather simple and personalised manner. Moreover, it seems that they prefer to use the simple quantitative tools to perform a quantitative risk analysis. Such a conclusion might need to be always considered when introducing any alternative to the existing tools. Laryea and Hughes (2008) concluded that the problem of the limited adoption of the existing tools can be dealt with through devising risk assessment methodologies that appreciate the actual practice in construction industry and reflect what practitioners do in reality. In fact, they suggested that introducing new models or methods may not necessarily be useful. Although such a position can be appreciated, it should not prevent researchers from investigating novel alternatives and devising usable DSSs that simulate the actual practice of the end users and allow them to express their personal judgement and utilise their cumulative experience. Yet, the tools need to be reliable and based on a firm theoretical base.

5. Summary and conclusions

This paper presented a review of the risk modelling and assessment literature published over the last five decades. It focused on the development of risk modelling and identified a number of proposals for improving the prevailing P–I risk model. It also discussed the different contributions towards investigating various theories and techniques for risk assessment. The presented review reveals significant results, which may be summarised as follows.

It was found that the P–I risk model still prevails, yet efforts have increased recently for improvement. The improvement proposals have accelerated recently and come into alignment with the increasing complexity of construction projects and construction risks. More sophistication is being incorporated into risk modelling and assessment in an attempt to reflect different aspects of complexity like the interdependencies between risks and the interaction between them and the surrounding project environment. The improvement proposals, however, are not comprehensive enough to capture, at the same time, the risk characteristics, the interdependencies between risks, the interaction with the complex project environment and the experience of the management teams. Indeed, understanding project vulnerability is crucial for advancing construction risk assessment. This is a novel approach for employing the practical experience of construction professionals for aiding risk assessment. It was found that there was an evident shift from perceiving risk as an estimation variance towards considering it as a project attribute. This shift was accompanied with a shift in assessing risk from using PT-based approaches towards using more analytical ones. In fact, the analytical approaches, that employ FST and AHP mainly, have recently dominated the literature. Progressively, sophisticated DSSs are being devised to facilitate the analytical and statistical tools and to handle the growing complexity of risk assessment. These DSSs enable conducting comprehensive analyses including risk identification, risk assessment, assessment aggregation and project risk level estimation. The review has confirmed what was previously mentioned that the literature lacks a comprehensive risk assessment framework which considers the different types of impact of a risk on different project objectives simultaneously. Such a framework is essential for obtaining realistic risk assessments which is the first step towards generating a realistic project risk level. Lacking a common scale was blamed for this limitation in literature. Although many authors have recommended ‘risk cost’ as a common scale for assessing risk impact on specific project objectives (Chan and Au, 2008; Dey, 2001; Franke, 1987; Paek et al., 1993; Sanchez, 2005; Williams, 1993, 1995), it was found that risk cost has never been used systematically for such a purpose. The review demonstrated that we lack an effective aggregation rule that generates a realistic project risk level without compromising the anatomy of the individual risk assessments. The conventional rules of aggregation, the averaging or the weighted sum, are not always suitable ways for obtaining a representative project risk level due to their underlying assumptions.

The paper has also reviewed the actual practice of risk analysis as published in the literature. The findings refer to a heavy reliance on practical experience and professional judgement when assessing construction risk. Moreover, the adoption of the available tools and DSSs is quite limited. Truly, this review has demonstrated a remarkable contribution of the researchers towards advancing risk modelling and assessment. It is unfortunate that there is still a wide gap between theory and practice. Yet, the existing body of knowledge demonstrates a firm basis from which to investigate novel alternatives that can bridge the existing gap between theory and practice. This paper recommends extending the P–I risk model and incorporating additional parameters to reflect the nature of the risk, the experience of risk analysts, the interdependencies between project risks and the influence of project environment on risk assessment. It also suggests using risk cost, as a common scale for measuring risk impact on various project objectives, within an analytical approach which structures and facilitates the experience and personal judgement of construction professionals for assessing construction risk. Risk cost, a percentage of project initial cost for instance, is believed to be a convenient and practical measure of risk impact as it is a common language understood by all construction parties. The simplicity of using risk cost for assessing risk and the facilitation of the practical experience are believed to be key virtues of the suggested approach. This may appeal to construction professionals and participate in advancing the real practice of risk assessment. This research is part of a wider research project aimed at rethinking construction risk modelling and assessment and facilitating closing the existing gap between theory and practice of construction risk assessment.

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Appendix A. Key papers in project risk modelling and assessment literature review

Phases	Number of papers	Year	Author(s)	Journal	Main tools & theories
The 1980s	8	1983	Barnes	IJPM	PT
		1983	Chapman and Cooper	JORS	PERT, OR tools
		1983	Diekmann	JCEM	MCS
		1985	Cooper et al.	IJPM	PT
		1986	Beeston	CME	MCS
		1987	Clark and Chapman	EJOR	PT
		1987	Franke	IJPM	LR, Cognitive argument
		1989	Kangari and Riggs	IEEETEM	FST
The 1990s	18	1990	Hull	IJPM	MCS, PERT
		1990	Al-Bahar and Crandall	JCEM	Influence diagramming, MCS
		1990	Yeo	JME	PERT
		1991	Mustafa and Al-Bahar	IEEETEM	AHP
		1992	Diekmann	IJPM	MCS, FST, Influence diagramming
		1992	Huseby and Skogen	IJPM	Influence diagram, MCS
		1993	Paek et al.	JCEM	FST
		1993	Tah et al	CSE	FST
		1994	Dey et al.	IJPM	AHP, PT
		1994	Riggs et al.	COR	AHP, Utility Theory
		1995	Williams	EJOR	Literature review (LR)
		1995	Zhi	IJPM	AHP
		1996	Williams	IJPM	LR, Cognitive argument
		1996	Wirba et al.	ECAM	FST
		1998	Dawood	CME	MCS, PERT
		1998	Tavares et al.	EJOR	PT
		1999	Mulholland and Christian	JCEM	PT, PERT
		1999	Ward	IJPM	LR, Cognitive argument

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Appendix (*continued*)

Phases	Number of papers	Year	Author(s)	Journal	Main tools & theories
The new millennium	13	2000	Chapman and Ward	IJPM	LR, Cognitive argument
		2000	Hastak and Shaked	JME	AHP
		2000	Tah and Carr	CME	FST
		2001	Baccarini and Archer	IJPM	LR
		2001	Ben-David and Raz	JORS	Optimisation through Microsoft Excel VBA
		2001	Dey	MD	AHP, Decision tree
		2001	Xu and Tiong	CME	Stochastic programming
		2001	Tah and Carr	JCCE	FST
		2002	Patterson and Neailey	IJPM	LR, risk register
		2003	Baloi and Price	IJPM	LR, Cognitive argument
		2003	Jannadi and Almishari	JCEM	LR, Cognitive argument
		2003	Ward and Chapman	IJPM	LR
		2004	Choi et al.	JCEM	FST
Post 2005	29	2005	Molenaar	JCEM	MCS
		2005	Shang et al.	ECAM	FST
		2006	Cervone	OCLC S&S	LR, Cognitive argument
		2006	Dikmen and Birgonul	CJCE	AHP
		2006	Poh and Tah	CME	Influence networks
		2006	Thomas et al.	CME	FST, Fault tree
		2007	Ackermann et al.	JORS	Theoretical argument, Risk Register
		2007	Aven et al.	RESS	LR, Cognitive argument
		2007	Cagno et al.	RM	LR, Cognitive argument
		2007	Dikmen et al. a	AIC	Case-Based Reasoning, Utility Theory
		2007	Dikmen et al. b	IJPM	FST, Influence diagramming
		2007	Dikmen et al. c	CJCE	ANP
		2007	Hsueh et al.	AIC	AHP, Utility Theory
		2007	Zeng et al.	IJPM	AHP, FST
		2007	Zhang and Zou	JCEM	AHP, FST
		2007	Zhang	IJPM	LR, Cognitive argument
		2007	Zou et al	IJPM	LR, Cognitive argument
		2008	Han et al.	AIC	LR, AHP
		2008	Zayed et al.	IJPM	AHP, Questionnaire
		2009	Cioffi and Khamooshi	JORS	PT
		2009	Luu et al.	IJPM	Bayesian Belief Networks (BBN)
		2010	Fung et al.	IJPM	Microsoft Excel
		2010	Mojtahedi et al.	SS	GTOPSIS
		2011	Hashemi et al.	JCEM	Bootstrap
		2011	Nieto-Morote and Ruz-Vila	IJPM	FST, AHP
		2011	Lazzerini and Mkrtchyan	IEEESJ	Fuzzy Cognitive Maps
		2011	Marle and Vidal	RED	Cognitive argument, Clustering heuristics
		2012	Fang and Marle	DSS	AHP, Simulation
		2012	Vidal and Marle	Kybernetes	Cognitive argument, Systems Theory

Abbreviation	Journal
AIC	Automation in Construction
BAE	Building and Environment
CJCE	Canadian Journal of Civil Engineering
CME	Construction Management and Economics
CSE	Computing Systems in Engineering
COR	Computers and Operations Research
DSS	Decision Support Systems
ECAM	Engineering, Construction and Architectural Management
EJOR	European Journal of Operational Research
IEEETEM	IEEE Transaction on Engineering Management
IEEESJ	IEEE Systems Journal
IJPM	International Journal of Project Management
JCEM	Journal of Construction Engineering and Management
JCCE	Journal of Computing in Civil Engineering
JME	Journal of Management in Engineering
JORS	Journal of the Operational Research Society
JSS	The Journal of Systems and Software
MD	Management Decision
OCLC S&S	OCLC Systems & Services

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Appendix (*continued*)

Abbreviation	Journal
RED	Research in Engineering Design
RESS	Reliability Engineering and System Safety
RM	Risk Management
SS	Safety Science

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