HARNESSING BIM DATA IN THE MANAGEMENT OF PROJECT RISKS: THE BAYESIAN RISK-BEARING CAPACITY APPROACH

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ABSTRACT: With the increasing proliferation of Building Information Modelling worldwide, an emerging issue is how to better leverage the BIM data in decision making. This research demonstrates formally that the cost information attached to BIM can be utilised to inform risk management decisions by incorporating the newly developed risk-bearing capacity approach into the Bayesian statistics framework. Under BIM, the deviations of outturn costs from planned costs can be systematically recorded and used to update the old "beliefs" that are normally formed by resorting to subjective probabilities. With the potential to integrate the data held by insurers, cost estimators and credit raters, this framework can greatly facilitate the effective use of enormous new data in improving risk management practices.

KEYWORDS: Project risk management, risk allocation, Bayesian approach, procurement system

INTRODUCTION

Infrastructure investment has been increasingly recognised worldwide as a significant driver for long-term economic growth. How an infrastructure project could unfold and end up is mostly shaped by project risk. According to Chinese Yin-Yan philosophy (Chan, 2008), whilst a risk may bring about hazards, it also creates opportunities. Actually, effective handling of risks could yield considerable financial rewards. Yet, the application of risk management is sometimes criticized as being an "add-in" instead of "add-on" to project management (Chapman and Ward, 2003). The focus is placed more on the passive setting of contingency funds than on the proactive handling of risks. The presence of this deficiency is not without a reason: the direct links between risk analysis and key procurement decisions are still not formally established, so when it comes to formulating risk responses, qualitative judgement generally takes preference over quantitative analysis in practice. The inadequacies of the current practice on risk management can be seen in the recommendations of a recent report by UK's Infrastructure Risk Group (Infrastructure Risk Group, 2013) with respect to the presentation of risk exposure, adjustment of optimism bias and integration of cost estimation and risk management. However, alongside the advent of Building Information Modelling (BIM), sensing instruments and robotics, infrastructure owners have much wider options than before to gather data with a lower cost. In recent years, BIM has been strongly advocated as the solution to the persistent coordination problem in fragmented construction supply chains. A great benefit of BIM is the data generated for project owners (e.g., Construction Operations Building Information Exchange (COBie)). A central question of this research is to what extent the new data can be harnessed to improve risk management in the procurement process. This research aims to demonstrate in a formal fashion that this knowledge gap can be filled by building a risk management framework around the risk-bearing capacity (RBC) approach (Chang, 2013, Chang, 2013, Chang, 2013, Chang, 2014, Chang, 2015).

According to a widely embraced project management framework, Gateway review process (Office of Government Commerce, 2007), the procurement of construction projects involves a series of important decisions, each of which should be confirmed before moving on to the next.

Whether the project is economically viable must be evaluated first (i.e., Gateway 1: Business Justification). Once the project's business case is deemed feasible overall, the next step is to decide the delivery strategy (i.e., Gateway 2: Procurement Strategy). After the completion of the tender, the business case should be updated to confirm that the project is still worthy of investment. All these decisions bear upon risk assessment. An integrated risk management framework should explicitly model how risk analysis evolves with design development and cost estimation and how it feeds into procurement decisions. Specifically, in the feasibility stage, the owner needs to evaluate whether the project's benefit is more than enough to cover the risk-adjusted cost. If not, the owner should consider offloading some risk to a third party by, say, taking an insurance cover. Currently, this decision is dominated by heuristic rules. A more rigorous method should be developed to determine the optimal cover whereby risk exposure can be efficiently reduced to an acceptable level. In the procurement strategy stage, the residual risks (that are uninsured at Stage 1) should be further handled by harnessing the contractor's capability of risk management through the choice of procurement systems and contract forms. This research demonstrates how risk analysis can be fully embedded into key procurement decisions at three important procurement stages. It is hoped that this framework can prompt attempts to facilitate a better integration of the rich data held by insurers, cost estimators and credit raters whereby procurement decision-making practices can move more towards sciences than arts.

LITERATURE REVIEW

Academic literature

The fascination with risk studies can be seen in nearly all scientific disciplines. Risks play a central role in understanding both natural and humanistic phenomena. The lasting interests in risk-related issues are also evidenced within construction/project management literature. The vast volume of academic works can be categorised into three groups:

1. Risk management framework

To guide the implementation of risk management, there exist several oft-cited risk management frameworks. The practical significance of risk management can be seen by the fact that most of the built environment professional bodies have either issued a risk management framework of their own (e.g., PRAM (Association for Project Management) and RAMP (Institute of Civil Engineers and Institute of Risk Management)), or contain a chapter on risk management in its Body of Knowledge (e.g., Project Management Institute). The extant frameworks bear a great resemblance to one another as they are all built around the logical steps of risk management: risk management planning, risk identification, (qualitative and quantitative) risk analysis, risk responses and risk monitoring. These guides are qualitative in nature and few details are provided to elaborate on the linkages of risk management's five steps. Working under a similar framework (called the SHAMPU framework), Chapman and Ward (2003) distinguish themselves by proposing the concept of risk efficiency as the goal of pursuit in risk management. When risks are treated as analogous to financial assets, a risk-efficient frontier can be constructed on the expected cost v.s. cost risk graph (p.40). All plans on the frontier are deemed risk efficient, indicating that they are the plans that "*provide a minimum level of expected risk for any given level of expected cost, or the minimum level of expected cost for any given level of cost risk*" (p.40). The problem of interest is to find an optimal trade-off between the expected cost and the cost risk. The authors suggest examining the cumulative probabilities of the cost under different risk plans. Some judgement should then be made in the selection of risk plans. Clearly this framework is a direct application of Markowitz's portfolio theory (Markowitz, 1991). However, the suitability of this application can be challenged. When framed as a stand-alone decision, the allocation of funds among asset classes should seek a balance of risk and return. This is where portfolio theory is instrumental. Yet, the selection of risk plans is not only a decision in its own right. What is more important is how to link this decision with the estimation of project cost so as to build the implication of this decision for the project's overall viability.

2. Risk analysis in project appraisal

The feasibility of the project is evaluated on the basis of its cash flows. The risk inherent in the variability of cash flows is chiefly reflected in the discount rate chosen, so the discounted cash flow approach is of deterministic nature (Mishra, Khasnabis and Dhingra, 2012, Ye and Tiong, 2000). In practice, it is very tricky to choose a rate that can fully capture the potential risk impacts (Kodukula and Papudesu, 2006), so Monte Carlo simulation is often employed as a complementary method in exploring the effect of stochastic factors (Chang and Ko, 2014). Simulation based techniques are also well suited to implement the framework developed in the current research.

3. Risk allocation decisions in general

Risk allocation has been a recurrent research issue within construction/project management literature since the 1980s with early works focused on the effect of contract form on risk allocation (Stukhart, 1984, Griffis and Butler, 1988, Ward, Chapman and Curtis, 1991). The analysis of risk-sharing decisions was formalized by Chapman and Ward (1994) using the expected utility approach. Chang (2014) advanced the formalization of this decision by considering the interaction of contracting parties using the Principal-Agent model to derive a formal condition for the optimal risk-sharing ratio in typical gain/painshare incentive schemes. Different from Chang (2014)'s theoretical effort, current research is more concerned with how to make improvements within the existing risk management framework.

Practical guides

Risk management has been recurrently revisited as an evolving practice. A recent attempt by UK's Infrastructure Risk Group is an example. Since the UK coalition government took power in 2008, infrastructure investment has risen to the top of government agenda. Infrastructure UK (IUK) was established as an agency under the HM Treasury in charge of the central planning and management of infrastructure projects. IUK set up a platform, known as the IUK client group, to facilitate the exchange between academic researchers and major infrastructure investors. One of the work streams of the IUK client group is to scrutinize current risk management practices. The publication of the report "*Managing Cost Risk & Uncertainty In Infrastructure Projects*" provides a list of nine useful recommendations (Infrastructure Risk Group, 2013), three of which bear direct relevance for the current research :

1. Present risk exposure as a range, to promote more informed decisions and communications (particularly at strategic-level);
2. Leading organisations to underpin early stage risk allowances with both reference class forecasting, and risk analysis, rather than Optimism Bias-based uplifts;
3. Consider cost and risk estimates side by side, for completeness and to combat double-counting.

The first two categories of recommendations set out the direction in which risk management practices should improve. In a nutshell, a genuine "add-on" risk management framework should at least satisfy five requirements:

1. Time-dependent

As the project design develops, cost estimation will get more precise. Risk analysis should provide a timely feedback to procurement decision makers regarding the feasibility of the project.

2. Sophistication
   An agreement is emerging among practitioners that the sophistication of risk management should be improved upon in two important aspects: first, point estimates (such as 10 percentile versus 90 percentile) are an inadequate basis for addressing risk impacts; second, the practice of optimism bias uplift is too crude and subject to gaming. The distribution of risk impacts should be better reflected in the formulation of business case;
3. Integration of cost estimation and risk analysis
   The result of risk analysis should reflect in the estimation of cost so that affordability can be reliably evaluated.
4. Employment of risk analysis to replace heuristic adjustments
   Optimism bias is a term used in the HM Treasury's appraisal book (HM Treasury, 2007) to reflect the combined impact of risks on cost creep. However, the mechanic adjustment by adding uplifts onto the base cost could contain excessive errors.
5. Explicit linkages of risk analysis and risk responses
   The purpose of risk analysis is to ground the evaluation of risk responses in quantitative assessment. The main challenge lies in how to factor risk analysis into procurement decisions.

These requirements serve as the guiding principles in the development of a new risk management framework.

RISK MANAGEMENT IN THE GATEWAY REVIEW FRAMEWORK

To make risk management fit more closely into the procurement process, an explicit link should be built for the quadruple connection of design development, cost estimation, risk analysis and procurement decision. An effective way to understand the current practice is through the review of existing guides, including RIBA (Royal Institute of British Architects) plan of work, RICS (Royal Institute of Chartered Surveyors) cost estimation guidance and OGC (Office of Government Commerce) Gateway review process. The key tasks that should be performed for these four elements at three pre-contract stages is synopsized in Table 1.

Risk management at Gateway 1

After the high-level strategic need of the project is confirmed at Gateway 0, the next decision is concerned with choosing the best technically feasible option and develop a business case that satisfies the criteria of strategic fit, achievability, affordability and value for money. At this stage, apart from ensuring the achievement of the project's strategic objectives, the most important procurement decisions are to check if the project cost will lie within the available resources and the preferred option is justifiable in cost-benefit terms. Risk is a pivotal factor in making these decisions.

In RIBA's plan of work, the purpose of this stage is to set out the key design parameters so as to evaluate the feasibility of the project. RICS suggests that, given the preliminary information, the cost just need be estimated to the right order of quantum (RICS, 2012). A convenient method is multiplying the size of area with the corresponding cost per unit area in estimating the cost ($C_{1,B}$) for building works and facilitating works (works needed to enable the project to commence, e.g., soil stabilisation works), as well as main contractor's preliminaries (costs associated with management and staff, site establishment, temporary services, security, safety and environmental protection), overheads and profit. The former, normally measured by gross external areas and gross internal floor areas, varies with several factors, including site areas, plot ratio, site coverage ratio, and height limit, while the latter is largely determined by site location, project type, construction method and inflation. So the estimation of base cost at Stage 1 (C_1^B) can be expressed as

$$C_1^B = AP + C_1^{ds} + C_1^{dl} \tag{1}$$

where A and P indicate the size of the facilities and the cost per unit area. The sum of design fees (C_1^{ds}) and development costs (C_1^{dl}) is then added onto the estimated works cost to form the base cost estimate.

The final step is to determine a contingency fund, known as the risk allowance, for the downside risks. In the OGC Gateway Review Process, risks should be classified by probability, impact, and ownership. Suppose that d types of random shocks $w_{1,l}$ (l=1…d) have been identified at Stage 1. RICS (2012) suggests that the owner set an allowance for four risk sources (design development risks, construction risks, employer change risks, employer other risks). By definition, risk allowance is referred to "*the amount added to the base cost estimate for items that cannot be precisely predicted to arrive at the cost limit.*" (RICS, 2012). It means that the nature of risk allowance is to avert the project being forced to stall when the downside risks eventuate. In principle, the risk allowance can be set in accordance with the expected loss resulting from the joint effect of risk sources, w_1,

$$Ew_1 = \sum_{l=1}^{d} Ew_{1,l} = \sum_{l=1}^{d} \mu_{1,l} = \mu_1 \tag{2}$$

w_1 is a random variable with mean μ_1 and standard deviation σ_1, i.e., $w_1 \sim \Phi(\mu_1, \sigma_1^2)$, where $\Phi(w_1)$ indicates the probability density function of w_1. As shown in the first quadrant of Fig.1, the average downside risk (μ_1) is a measure of risk allowance (RA). The owner can set a budget equal to the cost limit (CL_1), i.e.,

$$CL_1 = C_1^B + RA = C_1^B + \mu_1 \tag{3}$$

However, if there is a cap on capital expenditure imposed either by the management or by fund availability, the CL_1 may fall out of the acceptable level (C^T). Measures should be sought to mitigate risk. OGC guidance suggests that the costs of managing risks should be separately identified and included within the base estimate or as contingency funding. When time permits, designing out risks could be the most effective solution. Otherwise, insurances should be evaluated at this stage to lower the residual risk to an acceptable level.

Risk management at Gateway 2

At this stage, the central procurement decision is to choose an appropriate procurement system. For this purpose, a sketch design will be developed to specify site layout, building shape, and the number of storey. With these details, cost can be estimated on the basis of primary (functional/structural) elements j (j=1,….,n) (e.g., facilitating works, substructure, superstructure, internal finishes, fittings, furnishings and equipment) (RICS, 2012). The base cost estimate (C_2^B) should be updated in accordance with the so-called elemental costs, along with the design fees (C_2^{ds}) and development costs (C_2^{dl}). In other words,

$$C_2^B = \sum_{j=1}^{n} Q_j E_j + C_2^{ds} + C_2^{dl} \tag{4}$$

where Q_j and E_j indicate the quantity and unit rate of element j. With more information available, the client must also update the risk register and assess its financial impact. Suppose the number of risk types is increased from d to e ($e \geq d$) and the original random variables $w_{1,l}$ identified at Stage 1 are updated to $w_{2,l}$ with mean $\mu_{2,l}$. The expected loss of $w_{2,l}$ now becomes μ_2:

$$Ew_2 = \sum_{l=1}^{e} Ew_{2,l} = \sum_{l=1}^{e} \mu_{2,l} = \mu_2 \tag{5}$$

The new cost limit (CL_2) is therefore

$$CL_2 = C_2^B + \mu_2 \tag{6}$$

To enable procurement options to be compared on the equal footing, risks should be identified and evaluated for each procurement option. At this stage, the owner should choose which type of delivery system to employ as well as how much risk to transfer (to the contractor). Whilst these two mundane decisions have a bearing upon the project's overall risk exposure and viability, the linkage is not well established.

Risk management at Gateway 3

At this stage, the key decision lies in ensuring that the project is still worth undertaking after incorporating the information provided in the winning bid, particularly with respect to the cost information submitted. Under the traditional design-bid-construction system and management system, the BQ is prepared by the client's quantity surveyors/cost manager, while, under design-build, the quantification of the owner's requirements is carried out either by main contractor or trade contractors. At this stage, the element j is broken down into k types of components. For example, a foundation is an element which may encompass the components of excavation, disposal, concrete, reinforcement, and formwork.

$$C_3^B = \sum_{j=1}^{n} \sum_{k=1}^{m} q_{jk} p_{jk} + C_3^{ds} + C_3^{dl} \tag{7}$$

where q_{jk} and p_{jk} represents the quantities and unit price of the components k needed for producing the element j. As the number of components for an element may be different, for ease of notation, m indicates the largest number of components that an element has in the project.

In the BQ, the cost of measured works and risks are separately listed. *"The contractor is required to provide a lump-sum fixed price for taking, managing and dealing with the consequences of the identified risk should it materialise." (RICS, 2012).* Distinct from Stage 2, the price of risks should consider the risk premium that the contractor actually charges for disposing of risks. From Stage 2 to Stage 3, the number of risk types identified may increase from e to f ($f \geq e$) and the assessment of risk sources is then updated to $w_{3,l}$ (l=1…f) with mean $\mu_{3,l}$. It is essential for the client to decide on what proportion of the risks should be transferred (b_l). Under this risk allocation (b_1,….., b_f), the contractor is exposed to w_3^t

$$Ew_3^t = \sum_{l=1}^{f} Eb_l w_{3,l} = \sum_{l=1}^{f} b_l \mu_{3,l} \tag{8}$$

In practice, the contractor adds a mark-up on to the bidding price (Zyphur and Oswald, 2013). The mark-up is reflective of the risk premium requested by the contractor. The standard deviation of w_3^t is the combination of the standard deviations of individual risk sources:

$$\sigma_{w_3^t}^2 = \sum_{l=1}^{f} b_l^2 \sigma_{3,l}^2 \tag{9}$$

In Principal-Agent theory, the cost of this risk transfer (RP) can be approximately estimated by (Gibbons, 2005, Grossman and Hart, 1986, Grout, 1984)

$$RP = \frac{1}{2} \gamma \sigma_{w_3^t}^2 \tag{10}$$

where γ indicates the Arrow-Pratt coefficient of risk aversion. After the risk transfer, the client's cost limit (CL_3) should be revised to

$$CL_3 = C_3^B + \sum_{l=1}^{f}(1-b_l)\mu_{3,l} + \frac{1}{2}\gamma\sigma_{w_3^t}^2 \tag{11}$$

Limitations of the current practice

The risk management practices contained in the Gateway review process involve three technical issues that have not been fully resolved:

(1) How to set the acceptable level?
(2) How to incorporate risk impacts into decision making?
(3) How to evaluate the effectiveness of measures on risk reduction?

The risk-bearing capacity approach makes a departure from existing project risk management frameworks in its attempt to make explicit the link between risk analysis and risk responses. Under this approach, the ultimate goal is seeking the most efficient bundle of risk management measures on the basis of available information at different stages in order to provide the capacity needed to withstand the predicted level of risk exposure. To make it a genuine "add-on" to project management, what follows will demonstrate how to embed the RBC approach into the Gateway review process.

THE RBC APPROACH

A synopsis of the approach

In modern organizational economics, Klein, Crawford and Alchian (1978) make a pioneering contribution to the building of a theoretical framework for explaining governance choices in terms of quasi rent. Compared to economic rent which informs the worthiness of undertaking an investment, quasi rent provides guidance on the desirability of finishing off a transaction. By definition, it measures the return in excess of the minimum required by a contracting party to carry on with the transaction. Chang (2013) modifies this concept by interpreting it as a measure of the limit that contracting parties are willing to withstand during the construction process. As contract breakup is costly, any risk exposure over the risk-bearing capacity should be priced differently (Chang, 2013, Chang, 2014). Consequently, a central focus of risk management should be placed on how to avoid contract breakup through the efficient use of feasible measures. As previously discussed, there are four crucial risk management decisions: first, at Gateway 1, the client should consider insurances to ensure that the estimated cost limit lies within the acceptable range; second, the impact of procurement system on the owner's risk exposure should be evaluated at Gateway 2; third, strategies for risk allocation must be evaluated at Gateway 3; four, in the same stage, the use of financial protection measures (bonds (tender bonds, performance bonds), guarantees (parent company guarantees, produce guarantees), warranties (collateral warranties)) should be considered (RICS, 2012). In current practice, these decisions chiefly rely upon decision makers' experience and heuristic rules. Decisions on the use of these measures should be integrated so as to address the tradeoffs or compounding effects between them. The greatest strength of the RBC approach is its ability to incorporate risk analysis into these risk management decisions.

How the RBC approach works

The risk-bearing capacity of a project consists of two parts (Chang, 2013): the contractor's quasi rent and the client's quasi rent. The contractor is incentivized to complete the project for two reasons: should the project terminate, the resources dedicated for the project may become non-recoverable and the expected profit from the project would not materialize. For the former, in a recent empirical investigation of quasi rents in Chinese construction projects (Chang and Qian, 2015), the lock-in effect may arise when the rental contract of machines cannot be cancelled without penalties and key management personnel cannot be mobilized to other projects. For the latter, the achievable *ex ante* profit margin is sensitive to local market conditions, varying project by project. The degree of lock-in also declines with time. Chang and Qian (2015) set out a formula of the contractor's quasi rent for low-complexity and low-risk projects in the area of Suizhou, China:

$$Q^c = K \times (x + 5\%) \times (1 - y) \tag{12}$$

where K, x, y represent contract value, project margin and completion percentage, respectively. The percentage of sunk investment to contract value is assumed constant (5%) across projects. The plausibility of this assumption is justified through a careful selection of samples.

On the other hand, the ultimate reason of the owner's vulnerability lies in the difficulty and the attendant cost in replacing the original contractor（known as switching costs). A formula employed by Chang and Qian (2015) shows that there are three cost items:

$$Q^o = \frac{K}{T} \times 30 \times (1 - y) + K \times 8\% + K \times 5\% \times (1 - y) \tag{13}$$

The first element of switching costs is associated with the opportunity cost of delay as a result of retendering, which can be approximately measured by the product of average cost of delay per day (K/T; K: contract value, T: project duration) and the average length of delay (30 days). The second element is meant to capture the extra cost arising from the repeated setup on site (e.g., temporary works). Last, quality uncertainties left over in the disrupted project could add an extra 5% to the owner's overall cost. These three costs together comprise the extra bill that could fall to the owner in the event of project disruption. To avoid incurring these costs, the owner will show a greater tolerance for unexpected costs. This is why Eq.(13) can be deemed a buffer for downside risks.

As shown in Figure 1, where the random shock actually eventuates is crucial. The practice of setting a fund for the downside realizations is meant to avert the project being stalled owing to lack of funds. When cost overruns occur, the contractor will shoulder most of the impact in accordance with the agreed-upon risk-sharing rules until his buffer (quasi rent) has exhausted. At this point, the contractor could either back out of the contract or seek to recoup some of the loss by holding up the owner in the negotiation of change orders. Quasi rents have proven to be a crucial factor for the renegotiation outcome (Chang, 2013, Chang, 2012). Suppose the change order can yield a benefit v, but cost c. How the net benefit B (=v-c) is shared depends on the bargaining power of two parties. Chang and Qian (2015) derive a simple result using the Nash bargaining model,

$$\begin{aligned} b^o &= \frac{1}{2}(B - \Delta Q) \\ b^c &= \frac{1}{2}(B + \Delta Q) \end{aligned} \tag{14}$$

where b^o and b^c indicate the owner's and contractor's share of the surplus. From Eq.(14), it is evident that the owner takes a much smaller share, proportional to the quasi rent difference ΔQ (= $Q^o - Q^c$). It is worth noting that the benefit of a change order is relative to the "do nothing" option.

In practice, change orders are more often triggered by design errors or unforeseen uncertainties than by the attempt to create value. For example, without altering the foundation design, collapse could occur during the construction process, resulting in an extra 10 million pounds. In the original BQ, the elemental cost of foundation is 20 million pounds. The cost of new foundation design is estimated to be slightly higher, 22 million pounds. This change order has a nominal benefit of 8 million pounds (10-(22-20)=8). In principle, the price of this change order could lie in the range of 22m and 32m. Where the price ends up depends upon the two parties' bargaining power. Suppose that Q^o and Q^c are 12 million and 5 million. Given this assumption, the owner can only obtain 0.5m (= ½(8-(12-5)) of the 8m benefit, while the contractor can snap up the rest 7.5m. The renegotiation of this change order will greatly change the risk-bearing capacity of both parties. Whilst the 7.5m paid on top of the construction cost is excessive, the owner could prefer to accept it because in doing so he can avoid incurring the cost of 12m (Q^o). Certainly, to what extent the contractor would utilise his bargaining power is also affected by several factors (e.g., the owner's ability to revenge in the future projects, the intensity of completion in the contracting market and the contractor's order book), Eq.(14) can be employed as the prediction for the worst scenario. For this reason, in estimating risk-bearing capacity, there are two cases to consider:

Case I: No change order

If the owner make no post-contract changes, the contractor can only withstand the shock less than his quasi rent, which corresponds to the breakup probability $\boldsymbol{A^n}$ (=1- $\Phi(Q^c)$) (see Fig.2(a)). Identifying $\boldsymbol{A^c}$ is crucial in cost estimation, because the shock over the contractor's risk-bearing capacity will result in an additional breakup cost ($\boldsymbol{L}$). The average cost of shocks is

$$W^n = Ew = \int_{-l}^{Q^c} wf(w)dw + \int_{-l}^{Q^c} (L+w) f(w)dw \tag{15}$$

The expected cost of the project should lie within the cost limit (C^T)

$$EC^n = C^B + W^n \leq C^T \tag{16}$$

Case II: Change order

If the owner needs to change requirements post contract, as explained previously, the breakup probability will reduce to $\boldsymbol{A_c}$, which can translate into an extra risk-bearing capacity for the project (see Fig.2(b)).

$$W^c = Ew = \int_{-l}^{Q^c+Q^o} wf(w)dw + \int_{Q^c+Q^o}^{h} (L+w) f(w)dw \tag{17}$$

Suppose the probability of change orders is denoted by $\boldsymbol{\pi}$, the expected cost of the project becomes

$$EC^c = C^B + (1-\pi)W^n + \pi(W^c + (1+t)Q^o) \tag{18}$$

In Eq.(18), the expropriation of the owner's quasi rent can increase the risk-bearing capacity, but at a high price. As argued in transaction cost economics (Williamson, 1996), the process of rent transfer could prove particularly costly. For instance, high priced change orders arising from holdup demands could prompt disputes and erode the mutual trust base. Thus, the cost of holdup is more than its nominal value, i.e, $(1+t)Q^o, t \geq 0$.

In Eq.(18), both π and t are parameters under the owner's control. First, the owner can choose to accept the holdup demand (t=0) or resolve the disputes through an agreed-upon mechanism (t>0). Second, the probability of change orders can be controlled through management of the design process. For example, the level of detail (LOD) of a design primarily depends upon the resources spent on that design. In other words, designing out and change orders act as alternatives. The extra cost for "designing out" should be evaluated against the cost of the change order.

What the RBC approach can add?

The RBC approach can fit in to the current procurement process and create insights into procurement decisions in four respects.

Determining the feasibility of the project

Conceptually, risk allowance is a point estimate of the downside impact. In statistical inference, interval estimates are deemed superior to point estimates in the sense that the former contain more information. This is perhaps the reason why IRG suggests using interval estimates to replace point estimates and having the whole range of cost estimates stress tested to check the robustness of the project. Since the 2007 financial crisis, increasing attention has been paid to the default likelihood of financial institutions under extreme economic conditions. This method emerged as a means of examining one financial organization's capacity for bearing shocks. There is no doubt that a capacity-based framework is a constructive step forward. Yet, scenario based sensibility analysis can only test for a discrete combination of parameters. The RBC approach attempts to push project risk management further by shifting the focus towards managing the probability that the cost target can be achieved.

In current practice, risk allowance is geared for the average downside realization of w. The purpose of a contingency fund is to satisfy the payment demand when uncertain losses arise. Separate estimations of base cost and risk allowance is a convenient practice of budgeting. However, risk management should not be limited to "fire-fighting", but rather avoiding the fire breaking out in the first place and, if necessary, mitigating its impact.

At Stage 1, a central issue is seeking the best value-for-money design solution within the funding constraint. If the design involves too much risk, insurances should be considered to reduce the risk exposure. Under the RBC approach, the effectiveness of an insurance should be evaluated on the basis of its contribution to the increase in risk-bearing capacity against its cost (risk premium). At this stage, given the preliminary design information, the best estimate of the project's risk-bearing capacity is the contractor's profit included in cost estimation. Eq.(15) can be applied to estimate the expected cost. Suppose there is an externally imposed budget limit, C^T and the maximum risk allowance $C^T - C_1^B$ cannot cover W^n, so an evaluation should be made to check if insurances can reduce the risk exposure to an acceptable level. For ease of notation, the premium of insurance coverage ($f(\alpha)$) is quoted in a percentage of base cost (C_1^B), α. If this protection is used to cover the upper end of the exposure, the whole distribution of w can be split into three areas (see Fig.3): first, in $\boldsymbol{A_1}$, the outcome turns out to be favourable; in $\boldsymbol{A_3}$, the exposure is zero as it is covered by the insurance policy; in $\boldsymbol{A_2}$, the owner is still exposed to random shocks. All together, the risk exposure is changed to W^I

$$W^{c,I} = \int_{-l}^{h-\alpha C_1^B} wf(w)dw + f(\alpha) \tag{19}$$

The decision on insurances is seeking

$$\mathrm{Min}_{\alpha}\left[C_1^B + W^{c,I}\right] \tag{20}$$

$$\text{subject to } W^{c,I} \le C_T - C_1^B$$

How to incorporate risk impacts into decision making

In current practice, p.10 v.s. p.90 or p.5 v.s. p.95 are still widely used (Hillson, 2012). The purpose of contrasting two polar values is aimed at revealing the spread of risk outcomes, thereby informing procurement decisions. However, there is a case to argue that the whole distribution of possible outcomes should be considered. As demonstrated in Chang and Zhu (2014), using Monte Carlo simulation techniques together with off-the-self software @Risk, the RBC approach can be implemented to consider the effect of random shocks across its full range.

Linking risk analysis and risk responses (A)- procurement system selection

At Stage 2, the principal mission of risk management is to reveal the effects of procurement system selection on the owner's risk exposure. To make procurement systems comparable, it is essential to assume that the design is invariant across procurement systems (Ive and Chang, 2007). Under this assumption, the key research question is: how efficient is it to achieve the same design in terms of transaction costs? In theory, procurement systems could change the difficulty in remedying the undesirable outcome and thus affect the owner's control over the design and construction output. From the perspective of transaction cost economics, the procurement system should be aligned with project attributes (Chang, 2014). In current risk management literature, no consideration is made to the impact of procurement system selection on the project's risk exposure. By contrast, the RBC approach is able to capture this impact by evaluating its effect on the risk-bearing capacity.

Procurement systems differ in the degree of fragmentation: design-build is the most integrated system because the main contractor is responsible for both detail design and construction, the traditional method lies in the middle in that the design has been finished by the architect/engineering prior to tender, and the management system is more fragmented in the sense that the owner enters into a direct contractual relationship with trade contractors. Under an integrated procurement system, most of the work is undertaken by a single contractor, resulting in two effects: more resources dedicated to the project and a greater profit demanded by the contractor to compensate for the greater complexity of a larger-size work. Both of these factors lead to the contractor's quasi rent being the largest under Design-Build (see Table 2 for a comparison). For similar reasons, the owner will find it much more difficult to replace the Design-Build contractor in the face of greater information asymmetry, because of the longer time taken to retender the project, greater cost is incurred for repeated setup and higher premiums required by the replacement contractor. As a whole, under the Design-Build, the project has the strongest risk-bearing capacity. However, instead of the high RBC per se, it is the utilization of this capacity which holds the key to risk management improvement. According to the canon of transaction cost economics, getting governance structure right is a decision of "first-order" significance. Once the procurement system is chosen, risks should be evaluated by taking them as organizational constraints and risk responses formulated accordingly. There are important tradeoffs to consider: whereas employing Design-Build can make the project more resilient to cost shocks, the owner will be exposed to a greater holdup threat. The benefit (B^c) of utilizing the owner's quasi rent as part of the risk-bearing capacity can be evaluated by subtracting Eq.(18) by Eq.(16) and differentiating with respect to π

$$B^c = \frac{d}{d\pi}(EC^n - EC^c) = W^n - W^c - (1+t)Q^o$$
$$= \int_{Q^c}^{Q^c+Q^o} (L-w) f(w) dw - (1+t)Q^o \tag{21}$$

Eq.(21) reveals that the benefit of reducing the probability of change orders by one percentage point amounts to the cost savings arising from a lower probability of contract breakup (first term in integral) net of the total cost of rent transfer ($(1+t)Q^o$). B_c must be weighed against the marginal cost of achieving a lower breakup probability through increasing design maturity. There might be an efficiency ground for the owner to bid out the project with an incomplete design and then seek changes through renegotiations (Chang and Qian, 2015). Further effort should be made to study the optimal degree of incompleteness in design prior to tender.

Linking risk analysis and risk responses (B)- risk allocation decisions

At Stage 3, the focus of risk management is on the determination of the optimal risk transfer to the contractor. In principle, this decision is guided by the principle of allocating risks to the party who can best manage/control them. As this principle is subject to judgment, the decision in practice is normally down to bargaining, making the owner tend to overuse her *ex ante* bargaining strength. However, the nominal favourable term of transaction may not transcend into a desirable outcome owing to the presence of bargaining power reversal (Chang and Ive, 2007). Quantitative prescriptive advice will be instrumental in assisting the owner to achieve a higher efficiency of risk allocation. The RBC approach provides a framework for incorporating risk allocation decisions into cost estimation in an integrated way. For ease of exposition, the allocation of risk is reduced to the choice of a single risk-sharing ratio (b) for the aggregate risk $\boldsymbol{w}$, under which part of the risk exposure (bw) is borne by the contractor. This allocation will enable the contractor to withstand greater downside cost shocks, i.e., increasing the contractor's risk-bearing capacity to Q^c/b. Given the optimal insurance cover α^* obtained in Eq.(20), the owner's risk exposure after risk transfer can be revised to

$$W^{n,IR} = \int_{-l}^{Q_c/b} wf(w)dw + \int_{Q_c/b}^{h-\alpha^* C_{1,B}} (L+w) f(w)dw + f(\alpha^*) \tag{22}$$

Suppose, at this stage, the target cost C^T is still adhered to, so the objective function becomes

$$\text{Min}_b \left[C_2^B + W^{n,IR} \right] \tag{23}$$

subject to $W^{n,IR} \le C^T - C_2^B$

The Bayesian RBC approach

The quantifiability of the RBC approach would be increasingly important in the era of big data. In recent years, with the advent of new technologies, data is generated at an unprecedented speed in terms of volume, velocity, and variety. The emergence of big data can be clearly seen from several sectors in the built environment. First and foremost, the increasing installation of smart meters to buildings will fundamentally change the nature of energy consumption data available for analysis in frequency (increase from monthly to every 30 minutes) and the degree of detail (down to individual spaces). The sheer volume of new data does not only make it possible to improve building energy management through timely responses to anomalies or savings on the inspection cost of energy usage (Fitzgerald and Dwoskin, 2014), but also allows for reliable statistical relations to be established between energy consumption and its driving factors. Second, smart infrastructure has been promoted as a vision for the future of infrastructure management (The Economist, 2010). Establishing the internet of things through the deployment of low-cost sensors can make it more efficient to collect operating data.

New data sources aside, the prevalent application of building information modelling to construction projects will allow the causal links between cost performance and its determinants to be more systematically investigated. When design and construction information are recorded in electronic forms, the trajectory of variances in construction cost and operating cost can be well preserved for each stage, thereby enabling more advanced statistical techniques for the analysis of asset lifecycle performance. The probabilistic model of the RBC approach (Eq.(22) & (23)) heavily depends upon the reliability of inputted parameters to maintain its predictive power. With more data available, the model can be calibrated for a specific type of projects. In circumstances where historical data are not readily available, the parameters are normally estimated on the basis of experts' subjective assessment. There is evidence that, when properly used, subjective assessment of risks can assist the owner in making sound procurement decisions (Chang and Ko, 2014). Yet, it is beneficial to accommodate the information of real cost data into the estimation of parameters. The popularity of Bayesian statistics in scientific spheres evinces the significance of extracting insights from real data in advancing the understanding of natural and human phenomena.

As the RBC approach focuses on cost variance, it is useful to provide an account of how it could be measured. In each of the three stages of project procurement, the estimation of cost variance could be different, so formally the outturn cost variance of stage *r* from project *i*, $\tilde{w}_{r,i}$, can be defined as

$$\tilde{w}_{r,i} = \tilde{C}_i - C_{r,i}^B \tag{24}$$

where $\tilde{C}_i$ and $C_{r,i}^B$ represent the outturn cost and the base cost estimate at Stage *r* in project *i*. BIM models can provide both cost information and the details of design solutions and procurement arrangement, whereby the causal relationship between cost variance and its determinants can be more thoroughly established (Fig.4) and the cost variance calculated for a specific stage can be used to calibrate the parameters of random shock distributions for that stage.

In modelling project cost, the log-normal function is often employed (Wall, 1997), i.e.,

$$f(\tilde{w}|\mu,\rho) = \frac{1}{\tilde{w}}\sqrt{\frac{\rho}{2\pi}}e^{-\frac{\rho}{2}(\ln\tilde{w}-\mu)^2} \tag{25}$$

where μ and ρ are the parameters that control the location and spread of the distribution. The issue of interest is whether the observational data can help improve the reliability of the estimate for ρ. By virtue of the Bayes theorem, one can make inference on ρ in the posterior probability distribution ($f(\rho|\tilde{w}_{r,1},\cdots,\tilde{w}_{r,u})$) after observing the outturn costs.

$$f(\rho|\tilde{w}_{r,1},\cdots,\tilde{w}_{r,u}) = \frac{f(\rho)f(\tilde{w}_{r,1},\cdots,\tilde{w}_{r,u}|\rho)}{f(\tilde{w}_{r,1},\cdots,\tilde{w}_{r,u})} = \frac{f(\rho)f(\tilde{w}_{r,1},\cdots,\tilde{w}_{r,u}|\rho)}{\int_0^\infty f(\rho)f(\tilde{w}_{r,1},\cdots,\tilde{w}_{r,u}|\rho)d\rho} \tag{26}$$

In Eq.(25), the product of the prior on ρ ($f(\rho)$) and the conditional probability of $\tilde{w}_{r,1},\cdots,\tilde{w}_{r,u}$ for a given value of ρ ($f(\tilde{w}_{r,1},\cdots,\tilde{w}_{r,u}|\rho)$), is normalized by the marginal probability of the observed data given the model (prior and likelihood) (the integral in the denominator). The data collected ($\tilde{w}_{r,1},\cdots,\tilde{w}_{r,u}$) from *u* different projects can be incorporated into the prior knowledge of ρ through the likelihood function. Assume $\tilde{w}_{r,1},\cdots,\tilde{w}_{r,u}$ are identically and independently distributed from a lognormal process,

$$f(\tilde{w}_{r,1},\cdots,\tilde{w}_{r,u}|\rho)=f(\tilde{w}_{r,1}|\rho)\times\cdots\times f(\tilde{w}_{r,u}|\rho) \tag{27}$$

Thus, the likelihood function is

$$L(\rho|\tilde{w}_{r,1},\cdots,\tilde{w}_{r,u})\propto\rho^{\frac{u}{2}}\exp\left(-\frac{\rho}{2}\sum(\ln x-\mu)^2\right) \tag{28}$$

To make Eq.(25) analytically tractable, a popular solution is to search for a conjugate prior whereby the prior and posterior functions are in the same family of probability distribution. Fink (1997) suggests that a gamma distribution with hyperparameters α and β meets this condition, i.e.,

$$f(\rho|\alpha,\beta)=\begin{cases}\dfrac{\rho^{\alpha-1}\exp(\frac{-\rho}{\beta})}{\Gamma(\alpha)\beta^{\alpha}} & \text{where } \rho>0\\ 0 & \text{otherwise}\end{cases} \tag{29}$$

where $\Gamma(\alpha)(=(\alpha-1)!)$ indicates the gamma function. This prior can yield a posterior distribution with the same distributional form, but with a different set of hyperparameters (α' , β'):

$$\alpha'=\alpha+\frac{u}{2} \tag{30}$$

$$\beta'=\beta+\frac{1}{2}\sum_{i=1}^{u}\left(\ln\tilde{w}_{r,i}-\mu\right)^2 \tag{31}$$

In doing so, posterior inference is reduced to the updating of hyperparameters of the prior. In circumstances where there is no historical data, the evaluator can estimate the hyperparameters on the basis of subjective evaluation first and then use the Bayesian statistics to improve the reliability of these estimates for next projects.

Although conjugate priors provide a convenient venue to solve the posterior distribution, the degree of fit of the assumed form to the observed project cost data should be scrutinized. In some complicated cases, the integration of the marginal probability in Eq.(25) could involve tremendous computational difficulty. Along with the development of Markov Chain Monte Carlo methodology, the Bayesian method becomes readily applicable to a wide range of practical problems. It is also well suited to the implementation of the new risk management framework developed in the current research.

Numerical Example

The integration of risk management into procurement decisions can be illustrated using a numerical example.

Stage 1: Business Justification

A developer plans to build a riverside housing project in a Chinese metropolitan city. According to the planning permission granted, the total floor area is 10,000 m^2. The market survey reveals that, if the project is positioned for the top-end of the market, the housing units could cost 10,000 RMB per m^2 to build and can be sold for 13,000 RMB per m^2. The design fees and development costs are 2% and 1% of the estimated construction cost. The project may take 12 months to complete. Given these conditions, the base cost is estimated to be 103m RMB (Eq.(4)). Nominally, this project can yield a profit of 27m (130-103). Yet, the feasibility of this project is affected by uncertainty. The developer seeks to achieve break even by setting the cost target at 130m.

At this stage, fifteen risk sources have been identified. Assume that the aggregate risk exposure (w_1) is a uniform variable, varying in the range of 0 and 60m. On average, the target cost is not achievable because the mean value of the risk (30m) is over the profit buffer, 27m. To reduce this risk exposure to an acceptable level (27m), the owner considers insurances. The owner's concern rests with the incidence of high loss. Through a cover of S, the owner can reduce the exposure from 0~60 to 0~60-*S*. How much cover to take depends upon the price of insurances. In theory, the premium of an insurance cover is a function of the expected value and variation of potential claims (Buhlmann, 1985). To simplify, suppose the premium is approximated by $aS + bS^2$, where *a* and *b* are constants. The net benefit of the insurance cover is

$$\begin{aligned} \Delta W &= W^I - W \\ &= -\int_{60-S}^{60} \frac{w}{60} dw + aS + bS^2 \end{aligned} \tag{32}$$

The first-order condition of Eq.(32) yields

$$S^* = \frac{60(1-a)}{1+120b} \tag{33}$$

Substituting Eq.(33) into Eq.(32) can work out the net benefit of the optimal insurance cover easily. The value added by an insurance cover is sensitive to its price, which in turn is determined by two parameters (*a* and *b*). The combination (*a*,*b*) bears upon the magnitude and type of risk insured as well as the condition of local insurance market. In short, the focus is only placed on the effect of *a* (i.e., *b*=0). As shown in Figure 5, the reduction in insurance premium can increase the optimal cover (S^*). At the right-most end (*a*=1), the cost for transferring risk to the insurance company is exactly equal to the average loss (under which bearing the risk and having the risk insured make no difference to the owner), so the optimal cover is zero. However, when the insurance market can pool the risk more efficiently, leading to a lower premium (*a*<1), it will become increasingly desirable for the owner to purchase more insurance for reducing risk exposure. In the extreme case where the insurance company charges nothing for the cover (*a*=0), the owner will choose to insure against the whole range of uncertain possibilities ($S^* = 60$). The sensitivity of optimal insurance cover to premium can also be seen from the angle of cost savings (the red line in Figure 5). The net benefit of insurance does not reach the negative territory (i.e., cost savings) until the premium drops to *a*=0.5. Suppose the owner receives an insurance offer where *a*=0.4, the most efficient cover is $S^* = 36$, which corresponds to a saving of 8.4m. With this cover, the owner's risk exposure will fall back within the target cost (124.6 (=133-8.4) < 130).

Stage 2: Risk-sharing with the contractor

In this project, aesthetic standards take precedence over cost and delivery time. Also, the owner tries not to get too involved in project management. Given these considerations, the traditional method is chosen. A key procurement decision for the owner at this stage is seeking an optimal risk allocation with the contractor. To apply Eq.(22) and Eq.(23), both the contractor's quasi rent (Eq.(12)) and the client's quasi rent (Eq.(13)) should be worked out.

First, as shown in Eq.(12), the contractor's quasi rent contains two components: the contractor's expected profit is a standard item in the estimation of elemental costs. The developer's quantity surveyor must provide an estimate according to the risk transferred. Suppose most of the historical data upon which the surveyor draws judgement are from projects employing a standard contract that specify a 50:50 risk allocation. The average historical rate of profit, 5%, is believed to be applicable to the current project. Using Eq.(10),

$$5\% \times 103 = \frac{1}{2}\gamma b^2 \sigma^2 = \frac{1}{2}\gamma (0.5)^2 \left(\frac{60}{12}\right)^2 \tag{34}$$

From Eq.(34), the risk attitude of the contractors active in the market can be inferred to be γ=0.14. Given the cover taken at Stage 1, the risk exposure uninsured is in a section of the uniform distribution (0~24m) with mean 4.8 and variance 40. This means that the risk premium the contractor could charge is $2.8b^2$ $(= 1/2 \times 0.14 \times b^2 \times 40)$). Besides, the sunk cost is estimated to be 5% of the contract value. As the owner has no knowledge of when the cost shock may eventuate, the mean can be used in the estimation of the contractor's risk-bearing capacity, i.e.,

$$Q^c = 2.8b^2 + 103 \times 5\% \tag{35}$$

Second, the owner's quasi rent can be estimated by taking the expectation of Eq.(13) with the assumption that the risk could eventuate with equal likelihood at any point in time:

$$Q^o = 103 \times 1/2 \times (1/12 + 5\%) + 103 \times 8\% = 15.1 \tag{36}$$

Now the owner's problem is: With the contract breakup cost considered, what is the optimal risk-sharing ratio (b) given the insurance decision made at Stage 1 ($S^* = 36$)? At a risk-sharing ratio b, the contractor's quasi rent (Q^c) is $2.8b^2 + 5.15$. Whereas transferring part of the risk to the owner can increase the contractor's risk-bearing capacity from Q^c to Q^c / b, the owner has to pay $2.8b^2$ m for the risk premium. In addition, buying the cover of S^* will cost 14.4m $(= 0.4 \times 36)$. Since the total exposure is limited to the uninsured risk exposure, 24m, so $Q_c / b < 24$. The owner seeks to offload some risk to the contractor by

$$\text{Min}_\text{b} \ W^{n,IR} = \int_0^{Q^c/b} \frac{(1-b)w}{60} dw + \int_{Q^c/b}^{24} \frac{15.1 + w}{60} dw + 2.8b^2 + 14.4$$

$$\text{s.t. } Q^c / b < 24 \tag{37}$$

Subject to the constraint, minimum value occurs at *b*=0.22 where the risk exposure is reduced to 16.4m. If the base cost remains the same, the total expected cost at this stage is reduced to 119.4m from 123.1m.

Updating the estimate of h

Initially, the owner requires her quantity surveyor to provide an estimate (60m) for the upper bound of the uniform distribution (*h*). To enable comparison between projects, this estimate can be normalised by dividing it with the base cost estimate (i.e., 60%). Upon completion, the owner finds the outturn cost is 140m. In the meantime, the owner is able to collect data on other five similar projects: 20%, 30%, 35%, 45%, 50%. The owner wonders how to make the best use of this data. The Bayesian approach discussed previously is well suited to problems of this nature.

In this project, the random shock is uniformly distributed, so the likelihood function is

$$f(\tilde{w}_1,\cdots,\tilde{w}_u|h)=\begin{cases}\dfrac{1}{h^u} & \text{where } h>\max(x_i)\\ 0 & \text{otherwise}\end{cases} \tag{38}$$

As explained, the Bayesian inference can be simplified by assuming that the prior and posterior take the same distributional form. If the Pareto distribution is assigned to the prior *f*(*h*), the posterior is also a Pareto variable.

$$f(h|\alpha,\beta)=\begin{cases}\dfrac{\alpha\beta^\alpha}{h^{\alpha+1}} & \text{where } h>\beta\\ 0 & \text{otherwise}\end{cases} \tag{39}$$

The posterior $f(h|\tilde{w}_1,\cdots,\tilde{w}_n)$ can be derived using the Bayes theorem,

$$\begin{aligned} f(h|\tilde{w}_1,\cdots,\tilde{w}_u) &= \frac{f(h)\,f(\tilde{w}_1,\cdots,\tilde{w}_u|h)}{\int_0^\infty f(h)\,f(\tilde{w}_1,\cdots,\tilde{w}_u|h)dh}\\ &= \frac{\dfrac{\alpha\beta^\alpha}{h^{\alpha+1}}\times\dfrac{1}{h^u}}{\int_\beta^\infty \dfrac{\alpha\beta^\alpha}{h^{\alpha+1}}\times\dfrac{1}{h^u}dh}\\ &= \frac{(\alpha+u)\beta^{\alpha+u}}{h^{\alpha+u+1}}\\ &= f(h|\alpha+u,\beta) \end{aligned} \tag{40}$$

It is evident that the posterior is also a Pareto distribution with $\alpha'=\alpha+u$, $\beta'=\max(x_i,\beta)$. The restrictions for β' are necessary for Eq.(38) and Eq.(39) to be non-zero.

The estimate of *h* in this project (60%) can be taken as the mean of the prior, i.e., $\alpha\beta/(\alpha-1)=0.6$. In principle, there are indefinite combinations (α , β) satisfying this condition. A convenient choice is (2,0.3). This set of superparameters can be updated by the new data as $\alpha'=7(=2+5)$ and $\beta'=0.45$ (=max(0.2,0.3,0.35,0.45, 0.4,0.3). With two new superparamers in

Eq.(39), the mean should be updated to 0.53 ($= 7 \times 0.45/(7-1)$), which is the upper bound estimate of the uniform risk shock that the owner should use in the next project.

Conclusions

Risks play a central role in construction procurement decisions. Currently, the focus of risk management seems more concerned with the setting of a contingency fund for unexpected bills than with the active management of risk. A full integration of risk management into the procurement process is an essential step to evolving risk management into an add-on to project management. The new risk management approach should provide a framework to link up the chain effect of design development on cost estimation, risk analysis and procurement decision. This research demonstrates that the RBC approach provides a flexible avenue to build this framework whereby new data can be accommodated to improve the reliability of estimation using the Bayesian statistics.

As suggested by the IRG report, the collection of data on outturn costs should be more systematically attempted. For instance, the integration of rich information held by insurers (e.g., Lloyds Register) and cost estimators (e.g., the Royal Institute of Quantity Surveyors) could be of enormous benefit to improve the effectiveness of project management in general and risk management in particular.

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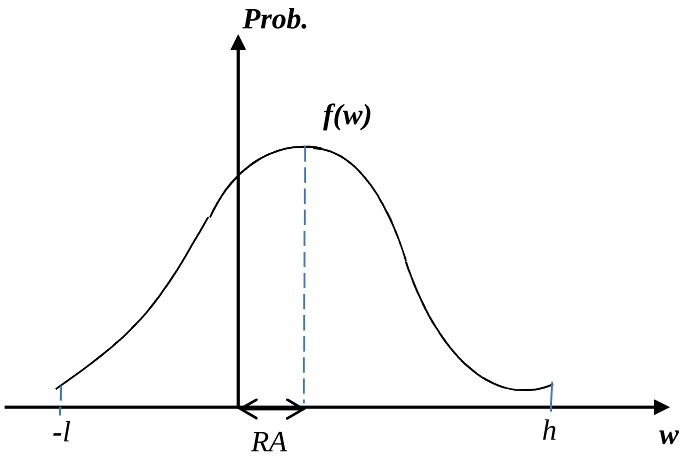
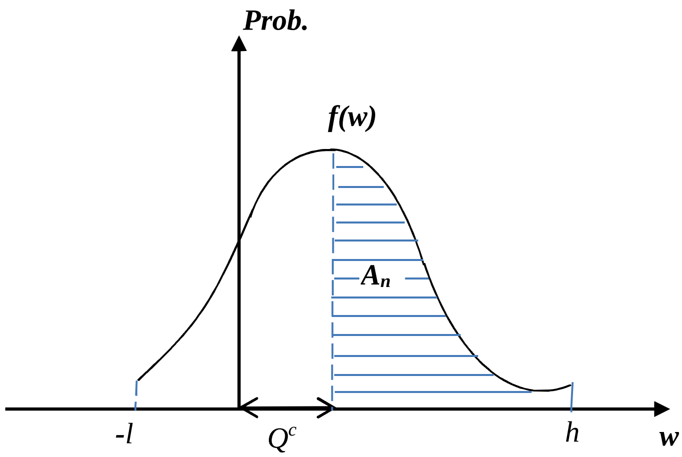
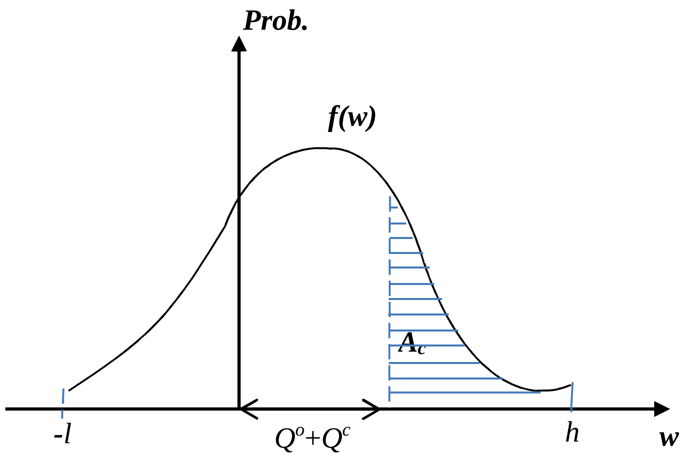


Figure 1 Relation of risk allowance and risk distribution



(a) No change orders issued



(b) Change orders issued

Figure 2 Breakup probabilities

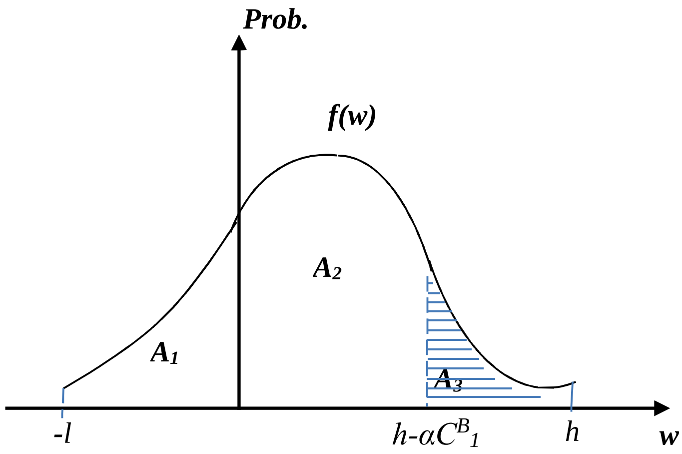


Figure 3 Effect of an insurance cover on the breakup probability

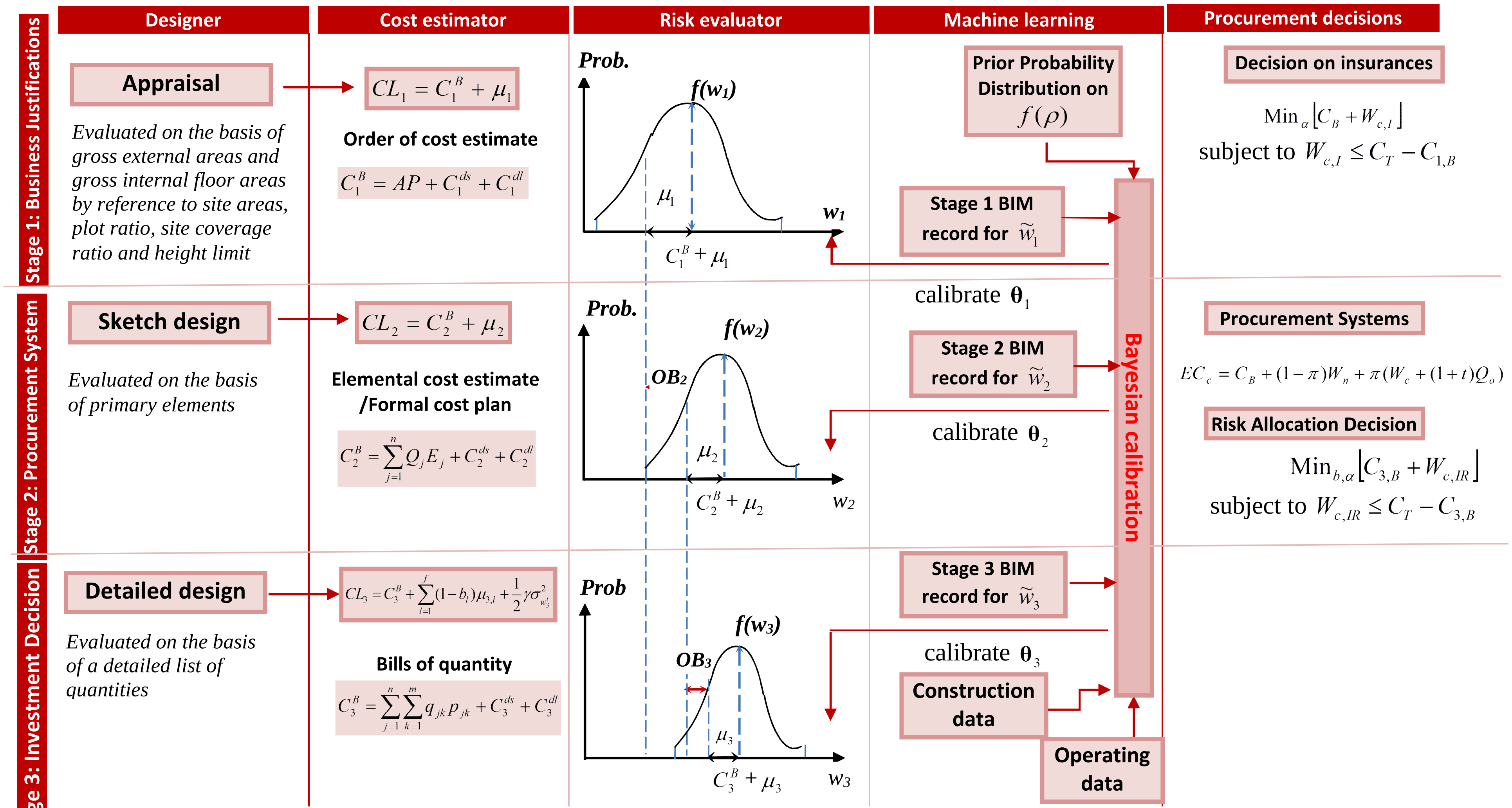


Fig 4 A Framework for Integrating Risk Management Into Procurement Decisions

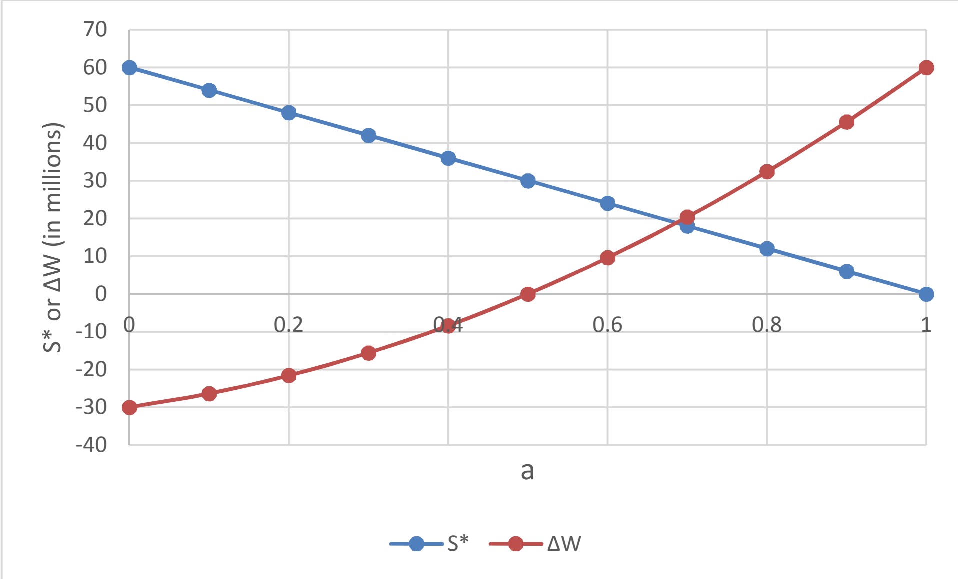


Fig. 5 The effect of insurance premium on the optimal risk cover and the net benefit of insurance

Table 1 Risk-bearing Capacity Risk Framework

Gateway stages	Gateway Review 1: Business justification	Gateway Review 2: Procurement strategy	Gateway Review 3: Investment decision
RIBA Plan of Work	**A: Appraisal**	**B: Design brief (sketch design)**	**C-E: Design (concept, design development, technical design)** **F-H: Pre-construction (production information, tender documentation, tender action)**
RICS Cost Estimating method	Order of cost estimate	Elemental cost estimate/Formal cost plan	Bill of quantities and Schedule of works (under the traditional method)
Key risk management tasks suggested by OGC's Gateway Review Process	•Risk management plans (management strategy and personnel) •Risks classified by probability, impact, ownership •Assessment of risk, costs and benefits to demonstrate appropriate balance of risk and reward in the preferred option •The costs of managing these risks separately identified and included within the base estimate or as contingency funding •Decisions on how residual risks are being insured •Evidence of similar projects or activities from which lessons may be drawn	•Major issues and risks logged, including strategic/political/ legislation •For construction projects, health and safety risks for the whole life of the project identified •Each risk assessed financially and included in business case either as sensitivity or a contingency •Risk management plans •Assessment of all technical risks documented, such as 'buildability' and risks associated with innovation •Risk transfer strategy, where applicable	•Risk and issue logs regularly reviewed, updated and acted upon •Updated risk management plans and risk log; client-side risk transfer plans •A business continuity and contingency approach •Contracts comply with OGC standard terms and conditions •Any changes to standard terms and conditions assessed •Analysis of risk transfer proposed by supplier or partner versus expectations or the original rationale for project •Plans for exit strategy at the end of the contract

	•Innovative solutions assessed by experts		
Key requirements of business case	•Project management process and project organisational structure •Project budget and timetable reports •Unproven assumptions included in risk assessment for next stage •Any issues concerned with the ability of the organisation to deliver and support business change should be registered at risk	**Strategic fit** **Options explored** **Value for money** •Bases for calculating costs and comparison of tenders agreed with key stakeholders •Updated business case on the basis of the full project definition, market assessment and initial benefits plan. •Procurement strategy reflected in business case •Examination of sensitivities and financial implications of handling major risks and assessment of their effect on project return **Affordability** **Achievability**	•Re-assessment of updated business case, including: strategic, economic, financial, commercial and project management factors •Key objectives revisited against final bid and proposed solution + confirmation that external factors have not affected current priorities •Cost/benefit/risk analysis against final bid information and results of evaluation, including sensitivity analysis

Source: Office of Government Commerce (2007a,b)

Table 2 Effects of procurement system on the contractor's and the owner's quasi rent

	Traditional Method	**Design-Build**	**Management System**
Contractor's quasi-rent	M	H	L
Sunk resources	M	H	L
Profit	M	H	L
Owner's quasi-rent	M	H	L
Opportunity cost of delay	M	H	L
Repeated setup cost	M	H	L
Quality risk premium	M	H	L