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FULL PAPER

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Calculation of risk costs in construction projects

Empirical analysis of construction risks applying the Monte Carlo method

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Abstract

As early as 1971, Schubert made a first contribution to the consideration of risks during the execution of construction projects. In addition to that, he was first to introduce elements of the risk management process to the construction management literature in Germany. By the use of an empirical study of the probability of risk occurrence and the cost amount by risk occurrence, Schubert made among others a statement about the importance of the risks depending on the amount of the risk costs. In an updated study for building construction projects with construction costs ≤2.5 million € and unit price contracts applying the VOB/B primarily the altered risk evaluations are shown; it needs to be emphasized that the sum of the determined risk costs corresponds to Schubert's results. Furthermore, with a variation of the characteristic attributes (response options) of the probability of risk occurrence and the cost amount by risk occurrence, it can be displayed that the risk costs during the execution of building construction projects are even considerably higher. Additionally, a probabilistic risk cost calculation — applying the Monte Carlo method — is used to reveal the bandwidth of risk costs. It can be pointed out that the risk costs range between 2.71% and 8.67% of the construction costs. The results could serve as a benchmark for contractors during the tender calculation to determine the amount of risk costs depending for example, on the market situation, the company-specific risk disposition as well as strategic considerations.

KEYWORDS

construction risks, cost estimation, Monte Carlo method, risk costs, risk management

1 | INTRODUCTION

Through his thesis in 1971 on the ascertainability of construction project risks during the tender and construction phase ("Die Erfaßbarkeit des Risikos der Bauunternehmung bei Angebot und Abwicklung einer Baumaßnahme"), Schubert made a substantial contribution to the identification and evaluation of risks in construction projects. In the course of that, he focused on individual risks of the contractor by the use of unit price contracts for public clients during the tender and construction phase of construction projects. The study is subdivided into three construction areas: building construction, civil engineering, and road construction.[1]

Schubert identifies 26 *individual risks [k]*, which he has had evaluated by contractors according to the *probability of risk occurrence in % of the number of projects [P_k]* and the *cost amount by risk occurrence in % of the construction costs [C_k]*. In this context, construction costs are defined as the remuneration for the agreed performance. The product of these results are the *risk costs of individual risks in ‰ of the construction costs [R_k]*, which provide the basis for the risk ranking.[1] The identified *individual risks [k]* of building construction projects according

TABLE 1 Risk costs according to Schubert, 1971[1]

Rank	Individual risk [k]	P_k	C_k	R_k
1	Delay due to weather conditions	14.8	1.59	**2.4**
2	Increase of material prices	13.1	1.49	**2.0**
3	Not calculated associated works (VOB/C)	11.9	1.55	**1.8**
4	Variation of quantities	11.4	1.44	**1.6**
5	Additional measures to meet the deadline	10.2	1.43	**1.5**
6	Change in wages according to the tariff	10.8	1.40	**1.5**
7	Insufficient compliance of preconditions by the client	11.6	1.31	**1.5**
8	More difficult nature of the subsoil than expected	8.9	1.54	**1.4**
9	Wage payment above the tariff	10.3	1.30	**1.3**
10	Delay in payment of the client	10.2	1.32	**1.3**
11	Extended employment of site set-up and human resources	10.1	1.30	**1.3**
12	Performance loss and additional measures due to weather conditions	9.0	1.33	**1.2**
13	Performance index for human resources and site equipment	8.5	1.44	**1.2**
14	Wrongly chosen average wage	8.4	1.23	**1.0**
15	Warranty claims	8.9	0.96	**0.9**
16	Coordination of subcontractors	6.6	0.89	**0.6**
17	Technical risk due to unusual design and so forth	4.3	1.19	**0.5**
18	Quotation for subcontractors	7.3	0.88	**0.6**
19	Defects and remedial work before acceptance	7.8	0.73	**0.6**
20	Obstruction of the construction process due to pipes and so forth	7.8	0.76	**0.6**
21	Risk of loss (§ 644 BGB)	7.4	0.84	**0.6**
22	Contractual penalties and corresponding receivables	3.7	1.00	**0.4**
23	Additional costs to meet the starting date	6.3	0.70	**0.4**
24	Legal disputes	4.4	0.79	**0.3**
25	Risks due to legal liability	4.7	0.62	**0.3**
26	Insufficient production planning of the contractor	3.8	0.57	**0.2**
			$\sum_{k=1}^{26}$	**27.2‰** (2.72%)
			Ø	**1.04‰**

Abbreviation: Figure following Schubert with deviating notations. C_k = cost amount by risk occurrence in % of the construction costs; P_k = probability of risk occurrence in % of the number of projects; R_k = risk costs of individual risks in ‰ of the construction costs.

to Schubert are shown in Table 1. The sum of the risk costs (2.72% resp. 27.2‰) and the average risk costs (1.04‰) are added.

2 | RESEARCH DESIGN

Due to the development of the construction industry since 1971, other results of the risk evaluation are to be expected.[2] Therefore, in this article, the updated study of Brokbals 2016[3] is presented. The research process is shown in Figure 1.

The development of the construction industry leads to the *first hypothesis*: If it is assumed that there was a development of the construction industry since 1971, then there is a change of (a) the risk ranking as well as (b) the amount of risk costs.[2] The *second hypothesis* is related to the characteristic attributes (Table 2) chosen by Schubert. If the characteristic attributes (response options) of the *probability of risk occurrence [P_k]* and the *cost amount by risk occurrence [C_k]* are variated in comparison to Schubert, the amount of risk costs changes once again. From these two hypotheses, two research objectives are deduced. The *first research objective* is the examination of the changed risk ranking and amount of risk costs in comparison to Schubert's study in 1971. The *second research objective* is the examination of the changed risk costs (and the risk ranking) due to the variation of the characteristic attributes.

To achieve the first research objective, the comparison with Schubert, it is necessary to ascertain the evaluation of the *probability of risk occurrence [P_k]* and the *cost amount by risk occurrence [C_k]* of the individual risks by using the same characteristic attributes as Schubert. This approach corresponds to a trend study. Considering though that Schubert completed his study 40 years ago, it is reasonable to substitute or modify some of the risks (*adaption 1*). Thereby, it needs to be emphasized that the number of 26 examined individual risks is maintained. Furthermore, the target population was

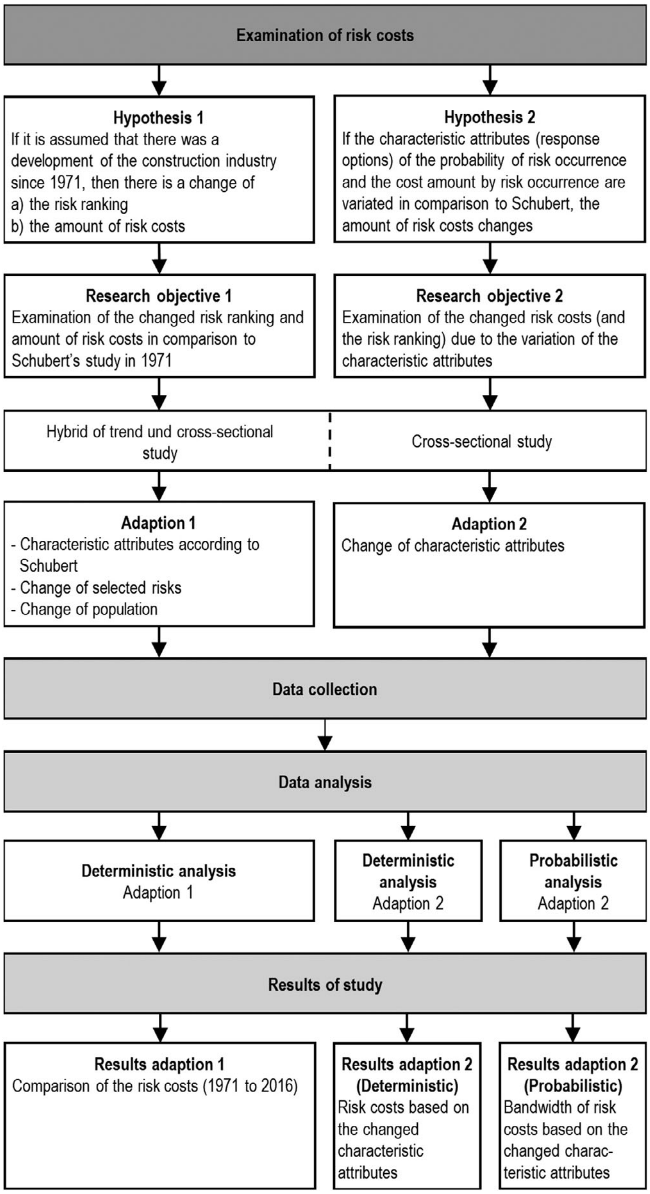

FIGURE 1 Research process[4]

changed, and the data are collected not only in Lower Saxony but all over Germany.

As a result of adaption 1, the presented study is not a pure trend study but a hybrid of a trend and cross-sectional study.[5] Nevertheless, it is convincing to use the results of the updated study for the comparison with the risk costs according to Schubert.

For the second research objective, the examination of the changed risk costs due to the variation of the characteristic attributes, *adaption 2* needs to be implemented. The characteristic attributes chosen by Schubert lead to partly just slightly differentiated *risk costs of individual risks* [R_k], whereby the risk ranking is aggravated. Consequently the characteristic attributes for the *probability of risk occurrence* [P_k] and the *cost amount by risk occurrence* [C_k] are partly modified (Table 2). Due to adaption 2, the study is a cross-sectional study.[5]

TABLE 2 Comparison of the characteristic attributes of Schubert 1971, Brokbals 2016 adaption 1 and 2[1,3,4,6]

	Characteristic attributes		
Characteristics	Schubert 1971	Brokbals 2016 (adaption 1)[a]	Brokbals 2016 (adaption 2)[b]
1. Probability of risk occurrence *(in % of the number of projects)*	< 5% 5% to 20% > 20%	< 5% 5% to 20% > 20%	< 5% 5% to 20% 20% to 50% > 50%
2. Cost amount by risk occurrence *(in % of the construction costs)*	< 0.5% 0.5% to 2% > 2%	< 0.5% 0.5% to 2% > 2%	No costs < 0.5% 0.5% to 2% 2% to 3% > 3%

[a]Pooled characteristic attributes (response options) for the comparison with Schubert 1971.
[b]Available characteristic attributes (response options) in the survey Brokbals 2016.

For the *data collection*, an online survey by building construction contractors is accomplished. Following Schubert only building construction projects with construction costs ≤2.5 million € and unit price contracts applying the VOB/B are examined. The contractors were asked to evaluate 26 individual risks according to the *probability of risk occurrence* [P_k] and the *cost amount by risk occurrence* [C_k]. Therefore, just the characteristic attributes (response options) of adaption 2 were available.

Altogether 24 out of 665 contacted contractors took part in the online survey. This equals a rate of return of 3.6%. In consequence of the low rate of return, the results of the study cannot be rated as generally valid and should be validated by a greater amount of data. Nevertheless, the results are suitable for a first preposition.

The *data analysis* is subdivided into the analysis for the research objective 1 and 2. For the research objective 1 only a deterministic analysis is completed. For the research objective 2, a deterministic and a probabilistic analysis are implemented to show the possible bandwidth of risk costs.

3 | RISK MANAGEMENT PROCESS

Schubert was first to introduce elements of the risk management process to the construction management literature in Germany.[7] By now several definitions of the risk management process coexist. The chosen definition depends on the aim of the particular paper.[8,9] The risk management process, which is referred to in this article, is presented in Figure 2.

The risk management process can be divided into the phases: “pre-tender phase”, ”tender phase”, “construction phase”, and “phase after project closure”. In this article, the risk management process during the tender phase is focused. If the contractor decides to compile a

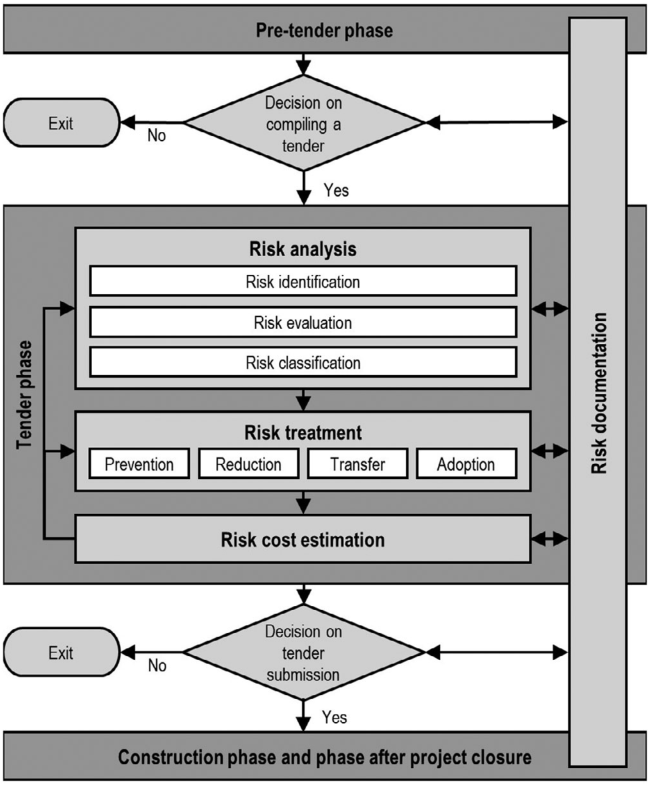

FIGURE 2 Risk management process during tender phase (Reference 6–15, complete figure in Reference 4)

tender, the risk management process of the tender phase starts. First, the *risk analysis* has to be accomplished. The goal of the risk analysis is to identify the risks that need treatment during the project.[8] Therefore, the risk analysis is subdivided into three subprocesses: risk identification, risk evaluation, and risk classification.

During the *risk identification*, the *individual risks [k]* of the project are captured and subsequently compiled in a risk list, which provides the basis for the following risk management process.[7,10,11]

Afterwards, in the course of the *risk evaluation*, a first appraisement of the *individual risks [k]* is made. Thereby both, the *probability of risk occurrence [P_k]* and the *cost amount by risk occurrence [C_k]* are evaluated *(eg, verbal classification: "very low" to "very high," numeric classification: 1–5 or absolute values)*. The product of these values results in the *risk costs of individual risks in ‰ of the construction costs [R_k]* (Equation 1).[1,7,11,12,16]

$$R_k = P_k \times C_k \times 1000 \tag{1}$$

R_k = risk costs of individual risks in ‰ of the construction costs; P_k = probability of risk occurrence in % of the number of projects; C_k = cost amount by risk occurrence in % of the construction costs.

The *risk classification* represents the interface between the risk evaluation and the risk treatment. The goal is to order the risks according to their priority. Due to this, the risk management process can be accomplished with a reasonable cost-benefit ratio.[10]

In the course of the *risk treatment*, the risks are examined for treatment alternatives, depending on their previous risk classification. A distinction is made between: risk prevention, risk reduction, risk transfer and risk adaption.

Afterwards the *risk cost estimation* for the *individual risk [k]* is accomplished. To estimate the risks one can use either the *deterministic* or the *probabilistic* risk cost estimation.[7,12,17,18] The deterministic risk cost estimation is a suitable method to obtain an overview of the *project risk costs of the individual risks [$R_{\text{Project},\,k}$]*. Therefore, in the first instance (Section 4.2.1), the project risk costs are estimated with this method.[7,18] The probabilistic risk cost estimation is explained in Section 4.2.2.

The *project risk costs of the individual risks [$R_{\text{Project},\,k}$]* are estimated by the use of Equation 2. Thereby, the decreased values for the *probability of risk occurrence [P_k]* and the *cost amount by risk occurrence [C_k]* due to the chosen risk treatment alternative should be considered if necessary.

$$R_{\text{Project},k} = \text{Construction costs} \times \left(\sum_{k=1}^{n} P_k \times C_k \right) \tag{2}$$

$R_{\text{Project},k}$ = project risk costs of individual risks [€]; P_k = probability of risk occurrence in % of the number of projects; C_k = cost amount by risk occurrence in % of the construction costs.

After the completion of the risk cost estimation, the management of the contractor decides, considering the risk situation of the project and other strategic deliberations, to submit a tender or not. In the case of tender submission, the risk management process is pursued in the construction phase. During the entire risk management process, the *risk documentation* needs to be accomplished.[10]

The results of Brokbals 2016 may serve as a benchmark during both, the risk evaluation and the risk cost estimation and as a consequence simplify the contractor's determination of the risk costs for the tender calculation.

4 | THE STUDY

4.1 | Data analysis and results — adaption 1

In the following, the risk evaluation of the contractors is analyzed and the *risk costs of the individual risks [R_k]* based on *adaption 1* are calculated. As the goal of this study is to examine the changed risk ranking and amount of risk costs in comparison to Schubert's study in 1971, for the first analysis, the characteristic attributes (response options) of adaption 2 are pooled so that they correspond to Schubert's characteristic attributes. Due to this, a comparison of the results is feasible. The *risk costs of the individual risks [R_k]* are calculated according to Equation 1. The detailed mode of calculation is presented in Reference 4.

In Table 3, the *risk costs of the individual risks [R_k]* referring to adaption 1 in comparison to Schubert's risk costs are presented. The risk costs are ranked based on the *risk costs of the individual risks [R_k]* and sorted by the results of Brokbals 2016 (adaption 1). At the lower end

TABLE 3 Risk costs of Brokbals 2016 (adaption 1) in comparison to Schubert 1971[1,3,4,6]

	Brokbals 2016 adaption 1		Schubert 1971	
Individual risk [*k*]	**Rank**	R_k	**Rank**	R_k
Obstruction caused by client (missing planning permission, schemes)	1	2.17	7	1.5
Changed and additional measures	2	2.11	-	-
Not calculated associated works (VOB/C)	3	1.87	3	1.8
Insufficient quotation for effort values	4	1.71	13	1.2
Insufficient quotation for subcontractors	5	1.42	18	0.6
Incomplete enforcement of claims for additional remuneration due to obstruction of prior contractors of the client	6	1.38	7	1.5
Insufficient quotation for on-site overhead	7	1.38	11	1.3
Insufficient quotation for wage costs (average wage)	8	1.34	14	1.0
Additional costs caused by delay in payment of the client	9	1.21	10	1.3
Additional costs caused by additional measures of the contractor to meet the deadline	10	1.19	5	1.5
Additional costs caused by delay of the contractor due to badly planned construction process, coordination, and interface management	11	1.16	16	0.6
Insufficient quotation for overhead expenses	12	1.01	-	-
Incomplete enforcement of claims for additional remuneration due to unexpected nature of the subsoil	13	0.95	8	1.4
Incomplete enforcement of claims for additional remuneration due to additional measures ordered by the client	14	0.95	-	-
Additional costs caused by delay of the contractor due to weather conditions	15	0.94	1	2.4
Additional costs caused by legal disputes	16	0.85	24	0.3
Insufficient quotation for material (increase of material prices)	17	0.80	2	2.0
Additional costs caused by warranty claims after acceptance	18	0.80	15	0.9
Additional costs caused by delay of the contractor due to insufficient construction performance	19	0.77	12	1.2
Loss of payment of the client (eg, due to bankruptcy, disputes about the amount of costs)	20	0.71	-	-
Additional costs caused by remedial works due to defects before acceptance	21	0.64	19	0.6
Insufficient quotation for site equipment costs	22	0.47	13	1.2
Additional costs caused by damage of the structure before acceptance (risk of loss § 644 BGB)	23	0.39	21	0.6
Not calculated change in wages according to the tariff	24	0.36	6	1.5
Additional costs caused by contractual penalties and corresponding receivables (compensation claim)	25	0.32	22	0.4
Insufficient tender price due to calculation or transcription error	26	0.23	-	-
$\sum_{k=1}^{26}$	**27.1‰** (2.71%)		**27.2‰**[a] (2.72%)	
Ø	**1.04‰**		**1.04‰**	

Abbreviation: *Rk* = risk costs of individual risks in ‰ of the construction costs.
[a]Sum corresponds to the initial sum of the risk costs according to Schubert without adoptions (cf. Table 1).

of the table, the sum of the risk costs $\left(\sum_1^{26} R_k\right)$ and the average risk costs (Ø) are added.

As a first result, hypothesis 1 can be verified. Due to the development of the construction industry, there is a change of (a) the risk ranking as well as (b) the amount of risk costs.

It needs to be emphasized that in defiance of the adaption 1, the results of the sum of the risk costs of Brokbals 2016 (adaption 1) are almost consistent with the initial sum of the risk costs according to Schubert (Brokbals 2016 (adaption 1): 2.71%; Schubert 1971: 2.72%).

4.2 | Data analysis and results — adaption 2

4.2.1 | Deterministic analysis

Also the second hypothesis can be verified, claiming that the amount of risk costs changes once again if the characteristic attributes

TABLE 4 Risk costs of Brokbals 2016 adaption 1 in comparison to adaption 2[3,4]

	Brokbals 2016 adaption 1		Brokbals 2016 adaption 2	
Individual risk [*k*]	**Rank**	R_k	**Rank**	R_k
Obstruction caused by client (missing planning permission, schemes)	1	2.17	1	3.63
Changed and additional measures	2	2.11	2	3.18
Not calculated associated works (VOB/C)	3	1.87	3	2.90
Insufficient quotation for effort values	4	1.71	4	2.25
Insufficient quotation for wage costs (average wage)	8	1.34	5	2.13
Additional costs caused by additional measures of the contractor to meet the deadline	10	1.19	6	1.99
Incomplete enforcement of claims for additional remuneration due to obstruction of prior contractors of the client	6	1.38	7	1.89
Additional costs caused by delay in payment of the client	9	1.21	8	1.80
Insufficient quotation for on-site overhead	7	1.38	9	1.75
Insufficient quotation for subcontractors	5	1.42	10	1.69
Additional costs caused by delay of the contractor due to badly planned construction process, coordination, and interface management	11	1.16	11	1.58
Insufficient quotation for overhead expenses	12	1.01	12	1.53
Incomplete enforcement of claims for additional remuneration due to unexpected nature of the subsoil	13	0.95	13	1.41
Incomplete enforcement of claims for additional remuneration due to additional measures ordered by the client	14	0.95	14	1.24
Additional costs caused by warranty claims after acceptance	18	0.80	15	1.23
Additional costs caused by legal disputes due to claims	16	0.85	16	1.18
Additional costs caused by delay of the contractor due to weather conditions	15	0.94	17	1.10
Loss of payment of the client (eg, due to bankruptcy, disputes about the amount of costs)	20	0.71	18	1.04
Additional costs caused by delay of the contractor due to insufficient construction performance	19	0.77	19	0.87
Insufficient quotation for material (increase of material prices)	17	0.80	20	0.87
Additional costs caused by remedial works due to defects before acceptance	21	0.64	21	0.75
Not calculated change in wages according to the tariff	24	0.36	22	0.52
Additional costs caused by damage of the structure before acceptance (risk of loss § 644 BGB)	23	0.39	23	0.51
Insufficient quotation for site-equipment costs	22	0.47	24	0.46
Additional costs caused by contractual penalties and corresponding receivables (compensation claim)	25	0.32	25	0.33
Insufficient tender price due to calculation or transcription error	26	0.23	26	0.26
$\sum_{k=1}^{26}$	**27.1‰** (2.71%)		**38.1‰** (3.81%)	
Ø	**1.04‰**		**1.47‰**	

Abbreviation: R_k = risk costs of individual risks in ‰ of the construction costs.

(response options) of the *probability of risk occurrence [P_k]* and the *cost amount by risk occurrence [C_k]* are variated in comparison to Schubert.

In Table 4, the results of adaption 1 in comparison to adaption 2 are shown. At the lower end of the table, the sum of the risk costs $\left(\sum_1^{26} R_k\right)$ and the average risk costs (Ø) are added. The calculation of the risk costs of adaption 2 is analogous to the calculation of the risk costs of adaption 1 except for the disposition of the characteristic attributes (Table 2).

Comparing the results of Schubert 1971 and Brokbals 2016 adaption 1 and 2, the following three differences need to be pointed out: (a) changed amount of risk costs, (b) changed risk ranking and (c) mostly increasing *risk costs of the individual risks [R_k]* and following increasing of the sum of the risk costs. Especially the increasing sum of the risk costs shall be highlighted:

- Schubert 1971: $\sum_{k=1}^{26}$ = 2.72% and Ø = 1.04‰
- Brokbals 2016 (adaption 1): $\sum_{k=1}^{26}$ = 2.71% and Ø = 1.04‰
- Brokbals 2016 (adaption 2): $\sum_{k=1}^{26}$ = 3.81% and Ø = 1.47‰

While the sum of the risk costs of Schubert 1971 and Brokbals 2016 (adaption 1) almost equal due to the unmodified characteristic attributes, the sum of the risk costs increases from 2.71% by +1.10%-points up to 3.81% of the construction costs. This equals an increase of about 40%. The risk costs according to Schubert 1971 and Brokbals 2016 (adaption 1) may be seen as a lower limit for the risk costs of a project within the set framework. Nevertheless, the results of Brokbals 2016 (adaption 2) lead to the assumption that the risk costs could be significantly higher.

4.2.2 | Probabilistic analysis

The target of the previously used deterministic analysis is to receive a specific value for the *risk costs of the individual risk [R_k]* to make the risk ranking and the comparison of the amount of risk costs possible. The deterministic analysis of risk costs is common in the construction industry.[17] Because of the vagueness by the evaluation of risks, the deterministic analysis is divergent to an accurate prediction of risk costs. By the use of the probabilistic analysis, a statement about the bandwidth of risk costs and the statistical certainty can be made. This enables the contractor during the tender calculation to choose the amount of risk costs depending for example, on the market situation, the company-specific risk disposition as well as strategic considerations.[19]

Although chances are not considered up to this point in the study, risks and chances should always be contemplated together. In this article, a common definition of risks and chances is used. Thereby, both risks and chances are a divergence from a desired value; chance is the positive whereas risk is the negative divergence.[12,20]

The desired value (chosen risk costs in the tender calculation) represents the reference level chosen by the contractor. The definition of the reference level is already discussed in the literature.[1,12] If a histogram of the risk costs is available for example, the median can be chosen for the risk cost estimation during the tender phase (Figure 3, at top). The certainty of overrun or shortfall of the reference level corresponds to 50% in each case. If the reference level is set higher or lower (Figure 3, bottom), the ratio between risk and chance postpones.[17] The choice of the reference level depends, among others on the market situation, the company-specific risk disposition as well as strategic considerations. In the course of this, the alternation of the chance-risk-ratio should be based on both, the economic success in the case of the acceptance of the tender and the success rate of the tender.[19,21] From experience, contractors usually choose a reference level with a high risk affinity dependent on the market situation.

A recommended method to accomplish a probabilistic analysis of risk costs is the Monte Carlo method. The principles of the Monte Carlo method can be looked up in Reference 22. For the study of Brokbals 2016, the following procedure is used:

- *Step 1*: Definition of the distribution function according to the online survey
- *Step 2*: Data fitting by the use of distribution fitting
- *Step 3*: Simulation of the *risk costs of the individual risks [R_k]*
- *Step 4*: Simulation of the *project risk costs of individual risks [$R_{Project,k}$]*

For *Step 1*, the relative frequencies of the selected characteristic attributes (response options) are used to define the distribution functions of *probability of risk occurrence (P_k)* and the *cost amount by risk occurrence (C_k)*.

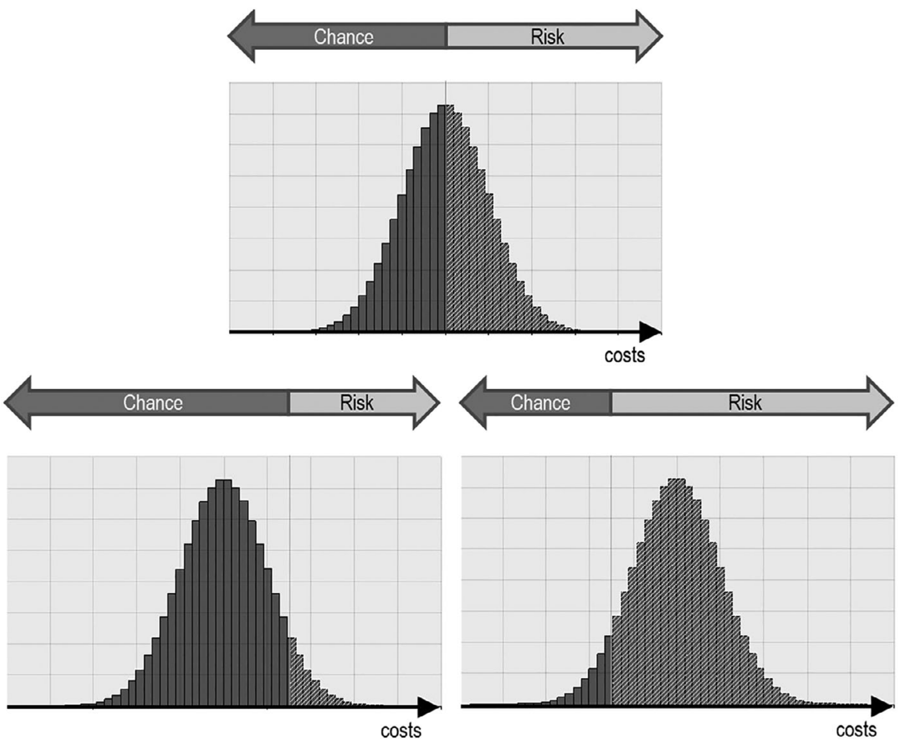

FIGURE 3 Choice of reference level[17,22]

During *Step 2*, the defined distribution functions are used to determine a theoretical distribution function by using the distribution fitting feature of the MS-Excel Add-in "@risk" by Palisade. The most suitable distribution functions are determined by the use of the Kolmogorow-Smirnow test (KS test), which is deployed for a small number of data. As a result, the following distribution function types are underlying the Monte Carlo simulation: (Beta)PERT-distribution, triangular distribution, uniform distribution, (generalized) beta distribution, and the Kumaraswamy distribution.

In *Step 3*, the *risk costs of the individual risks [R_k]* are calculated by multiplying the fitted distribution functions of the *probability of risk occurrence (P_k)* and the *cost amount by risk occurrence (C_k)*.

At last, in the course of *Step 4*, the project *risk costs of individual risks [$R_{Project,\ k}$]*, as the sum of the *risk costs of the individual risks [R_k]*, are simulated. The simulation consists of 100.000 iterations.

The results of a Monte Carlo simulation are usually depicted as a histogram and/or a cumulative curve. The histogram's abscissa shows the risk costs in percentage of the construction costs whereas the ordinate depicts the corresponding frequency. At the top of the histogram, one can see two sliders, which can be used to depict the overrun or shortfall probability of specific values.[20]

The histogram can be converted into a cumulative curve. The slope of the cumulative curve reveals the frequency in the value range; the steeper a curve the more likely is the probability that values occur in this value range.[19]

In Figure 4, the results of the Monte Carlo simulation for the *project risk costs of individual risks [$R_{Project,k}$] in % of the construction costs* are presented. The results are depicted as a histogram and cumulative curve. The sliders are attuned to the quantiles $Q_{0.05}$ and $Q_{0.95}$. It can be pointed out that, with a probability of 90%, the risk costs are in-between 2.71% and 8.67% of the construction costs. Following the risk costs will not overshoot 8.67% of the construction costs with a probability of 95%.

In Table 5, additionally the quartile $Q_{0.05}$, the median ($Q_{0.5}$), the arithmetic average (μ), the quartile $Q_{0.95}$, the SD (σ) as well as the arithmetic average ± SD (μ ± σ) according to the above-mentioned histogram (resp. cumulative curve) are shown.

It should be noted, that the arithmetic averages of the deterministic and probabilistic analysis differ because of the chosen fundamental assumptions (further explanation in Reference 4 and 22).

As a result of the comparison of Schubert 1971, Brokbals 2016 adaption 1 and adaption 2, it has been concluded that the risk costs of 2.71% according to Brokbals 2016 adaption 1 (resp. Schubert 1971: 2.72%) may be seen as a lower limit for the risk costs of construction projects within the framework set in this paper (Section 4.2.1). The results of the probabilistic analysis of Brokbals 2016 (adaption 2) confirm the conclusion that risk costs of 2.71% may be seen as a lower limit as the quartile $Q_{0.05}$ (2.71%) of the probabilistic analysis equals the result of Brokbals 2016 (adaption 1).

Altogether, the results of the probabilistic risk cost estimation signalize the importance of considering the amount of risk costs in the tender calculation. If, for example, the calculated profit in the tender calculation is between 2% and 3% of the construction costs, the risk costs (assuming that the chances, which need to be deducted, are mostly lower than the risks) will reduce the calculated profit or even cause a negative project outcome in many cases.

TABLE 5 Results of the Monte Carlo simulation ($R_{Project,\ k}$) — Table[22]

$Q_{0.05}$	2.71%
Median $Q_{0.5}$	5.04%
Arithmetic average μ	5.28%
$Q_{0.95}$	8.67%
SD (σ)	1.84%
μ - σ	3.44%
μ + σ	7.12%

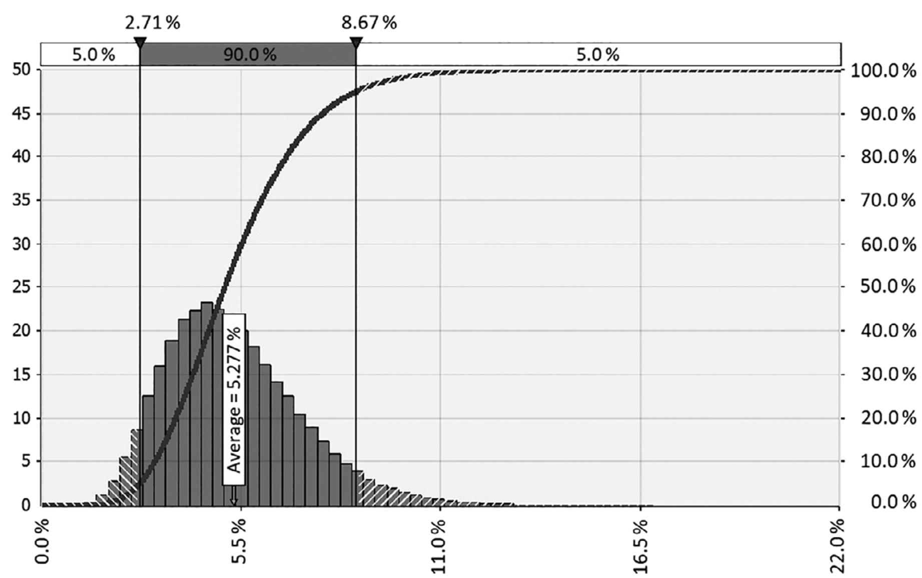

FIGURE 4 Results of the Monte Carlo simulation ($R_{Project,k}$) — histogram[22]

5 | CONCLUSIONS

The results of the first analysis unveil that the development of the construction industry over the last 40 years had influence on both, the risk ranking and the amount of the risk costs of the individual risks in comparison to Schubert. Although, it needs to be emphasized that the sum of the risk costs corresponds to Schubert's results (Schubert 1971: 2.72%, Brokbals 2016: 2.71% of the construction costs).

Due to the second analysis, with variated characteristic attributes, changed risk costs were presented. The sum of the risk costs increased from 2.71% by +1.10%-points up to 3.81% of the construction costs, which equals an increase of 40%. The following probabilistic analysis — applying the Monte Carlo method — is used to determine the bandwidth of the risk costs and their probability of occurrence. With a probability of 90%, the risk costs are in-between 2.71% and 8.67% of the construction costs.

The determined (bandwidth of) risk costs may serve as a first benchmark for contractors during the tender calculation. Due to the low rate of return, the results cannot be seen as generally valid and need to be validated by a greater amount of data. Nevertheless, the results may help to determine the amount of risk costs depending, for example, on the market situation, the company-specific risk disposition as well as strategic considerations.

During further research, the study may be extended for both, civil engineering and road construction projects as well as for additional contract types, resulting in a differentiated risk profile for various project types, which contributes to the contractor's project-specific risk awareness.

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