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From Contract Amendments to Risk-Calibrated Duration Multipliers: A Statistical Framework for Realistic Construction Contract Planning

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Abstract

Construction contract durations are fixed during procurement, yet delivery often changes after risks materialize and formal extensions of time are approved. Although delays, extension-of-time claims, change orders, and risk-based duration estimation are well studied, less is known about how contract-amendment records can be converted into duration multipliers for planning. This paper develops a quantitative, document-based Risk-Calibrated Duration Multiplier framework linking initially contracted duration, approved extensions, and documented risk causes. The framework was applied to 197 signed works contracts from 60 projects within a broader portfolio of 63 EU-funded water and wastewater infrastructure projects, predominantly administered under FIDIC Red and Yellow Book conditions. The analysis combined duration multipliers, impact-weighted attribution of multi-risk amendments, risk-time coefficients, bootstrap uncertainty assessment, concentration indicators, benchmark regression models, and reconstruction validation. For completed contracts, the mean multiplier was 1.372, with P50, P80, and P90 values of 1.233, 1.635, and 1.886. Public-law procedural and design risk categories accounted for 60.9% of the total extension premium. The results show that contract-amendment records can be transformed into statistically interpretable planning parameters and used as a portfolio learning and contract-governance tool for more realistic infrastructure contract planning.

Keywords: contract amendments; construction contracts; duration multipliers; FIDIC; infrastructure projects; planning; risk management



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1. Introduction

Infrastructure projects are among the most complex and risk-sensitive forms of construction investment. They typically involve long planning and implementation periods, multiple public and private stakeholders, demanding technical interfaces, public funding constraints, regulatory procedures, and external conditions that cannot be fully controlled at the time of procurement. In such projects, time performance is not only a scheduling issue; it also affects contract administration, funding eligibility, public-service delivery, environmental compliance, and the credibility of infrastructure programs.

Once the duration of a works contract is defined during procurement and incorporated into the contract, it becomes a binding obligation for the contractor and a planning assumption for the employer, supervising engineer, funding bodies, and end users. However, the initially contracted duration of construction works is often fixed before all design, permitting, site, market, coordination, and institutional risks have been fully revealed. This creates a structural tension between deterministic contract planning and the probabilistic nature of construction delivery. When such risks materialize, their time effects are often documented and formally recognized through contract amendments that grant extensions of time.

As synthesized in Section 2, existing studies have examined construction delays and schedule overruns [1–6], extension-of-time claims and contract administration [7–16], change orders and contract amendments [17–24], risk management, risk assessment, and advanced risk-modeling approaches [25–31], and data-driven duration prediction [32–38] from several perspectives. Collectively, these streams show that time overruns are recurrent, delay causes can be classified, extension-of-time claims require formal documentation, and risk-based duration estimation is an active research field. However, limited methodological guidance exists on how formally approved contract-amendment records can be converted into risk-calibrated duration multipliers for future works-contract planning. This study addresses that limitation by linking three elements that are usually treated separately: approved extensions of time, the risks documented as their causes, and the initially contracted duration. By doing so, it turns retrospective contract-administration evidence into a basis for estimating realistic time allowances before comparable works contracts are procured.

The study addresses the following research questions:

- RQ1: Which materialized risk categories are most frequently associated with formal extensions of construction works contracts, and which categories contribute most to the approved extension duration?
- RQ2: How can extension-related amendment records be transformed into contract-level duration multipliers and risk-specific time premiums?
- RQ3: Which statistical procedures are suitable for estimating, validating, and expressing uncertainty in risk-calibrated duration multipliers?
- RQ4: How can the proposed methodology support more realistic planning and management of comparable future infrastructure works contracts and contract portfolios?

To answer these questions, the framework was applied to 197 signed works contracts from 60 projects within a broader portfolio of 63 EU-funded water and wastewater infrastructure projects in Croatia. The contracts were predominantly administered under FIDIC Red and Yellow Book conditions. For completed contracts, the mean duration multiplier was 1.372, with P50, P80, and P90 values of 1.233, 1.635, and 1.886, respectively. The risk-time decomposition showed that public-law procedural and design-related risk categories accounted for 60.9% of the total extension premium, while the leave-one-contract-out reconstruction reduced mean absolute error by 35.5% relative to a portfolio-mean benchmark.

The paper makes two main contributions. The theoretical contribution lies in developing the Risk-Calibrated Duration Multiplier (RCDM) framework as a conceptual and analytical approach for linking risk materialization with more realistic construction contract duration planning. Rather than focusing only on the classification of delay causes, the framework shows how approved time extensions can be translated into calibrated duration multipliers and risk-time coefficients. The practical contribution is that these coefficients are transparent, easy to interpret, and can be derived from contract-administration data that contracting authorities already generate during regular project delivery. This makes the approach relatively low-cost, replicable, and suitable for early implementation in public-

sector project environments, while still allowing for further development in organizations with more advanced digital, analytical, or project-management capacities.

2. Literature Review

The literature review was developed as a structured narrative synthesis of the main research streams relevant to construction contract duration. The selected studies were chosen for their thematic relevance to construction delays, extension-of-time claims, change orders, contract amendments, risk management, data-driven duration estimation, and infrastructure delivery. The purpose of this section is to position the proposed framework within existing research, rather than to provide a bibliometric inventory of all delay-related studies. The review therefore focuses on how previous literature treats three elements that are central to this paper: approved extensions of time, documented risk causes, and initially contracted duration.

Construction delays and schedule overruns have been widely studied as recurring outcomes of construction-project complexity. Broad reviews and meta-analytical studies have identified delay causes such as financial difficulties, slow decision-making, design changes, poor coordination, labor and material shortages, contractor-related issues, public-authority delays, adverse weather, and other external conditions [1–3]. Other studies have connected delay causes with project-management systems, digital tools, and integrated delivery approaches, showing that delay analysis increasingly intersects with data-driven construction management and decision-support methods [4]. At the infrastructure level, large projects are particularly exposed to schedule and cost deviations because they involve long delivery periods, multiple stakeholders, technical interfaces, public decision-making, and institutional uncertainty [5,6,39,40]. This stream of literature establishes that construction delays are not isolated exceptions but recurring and classifiable phenomena. Its contribution is primarily diagnostic: it explains why delays occur and how delay causes can be grouped, but it does not usually convert formally approved time-extension outcomes into duration multipliers for future contract planning.

A second stream of literature concerns delay analysis, extension-of-time claims, and contract administration. Delay-analysis methods have been developed to support construction claims, the selection of forensic techniques, and the substantiation of time entitlements [7–9]. Decision-support systems have also been proposed to assist with extension-of-time entitlements and to reduce inconsistencies in claim assessment [10]. More recent contract-administration studies have examined extension-of-time provisions under national and international standard forms of contract, including design-build forms and FIDIC-related contractual frameworks [11,12,14,15]. In parallel, BIM-based and knowledge-driven claim-management systems have been developed to improve the documentation and governance of extension-of-time claims [13,16]. These studies are directly relevant because they show how delay events are documented, assessed, and administered contractually. Their focus, however, is mainly retrospective: they address whether an extension of time is justified, how it should be evaluated, or how claims should be managed after a delay event has occurred.

Change orders, variations, and contract amendments form a closely related research stream. Earlier empirical work on public works projects showed that change orders can be statistically analyzed and that their causes can be categorized using recorded project data [17]. Subsequent studies examined the relationship between change orders, cost growth, schedule growth, and construction intensity in public infrastructure and building projects [18,19]. In design-build infrastructure projects, including highway and water/wastewater projects, change-order records have been used to compare schedule performance across project types [20,23,24]. Recent studies on variations and claims further

confirm that contract changes remain an important source of time, cost, and dispute-related consequences in construction projects [21,22]. This literature is particularly close to the present study because it demonstrates that contractual change records are valid empirical data. Nevertheless, most change-order studies focus on occurrence, causes, and performance impacts. They rarely use amendment-level extension records as the basis for deriving risk-specific duration coefficients and portfolio-level multiplier benchmarks.

Risk-based and data-driven duration estimation has also developed substantially in recent years. Construction-risk modeling has moved from probability–impact matrices toward probabilistic, simulation-based, fuzzy, statistical, and data-driven approaches [25,26]. Simulation-based schedule-risk analysis has been used to estimate delay risk and assess the probability of timely project completion [32], while fuzzy modeling has been applied where duration uncertainty is difficult to express through precise probabilities or deterministic values [33]. Machine-learning methods have been used to predict delay risk and construction duration from historical project data [34,35]. Early-stage duration models have also been developed for planning and tender-preparation phases using project characteristics and statistical indicators [36–38]. Recent construction-risk literature further emphasizes data-driven and AI-supported risk assessment, while also recognizing the continued importance of context-specific interpretation and expert judgement [27–30]. These approaches provide important foundations for risk-informed planning. Their empirical inputs, however, are often expert assessments, activity-level risk models, general project characteristics, or predictive algorithms. Less attention has been given to approved contract amendments as documentary evidence of risks that actually materialized and were formally recognized as grounds for extending contract duration. The practical adoption of advanced risk and duration-estimation methods is also an important consideration. More sophisticated approaches, including complexity-driven risk-path modeling, can provide valuable analytical insight into the interaction between project complexity and risk propagation [31]. However, implementation in ordinary project environments may depend on the availability of structured data, modeling expertise, organizational support, and the maturity of risk-management practices. Recent construction-risk assessment research also shows that many organizations still rely heavily on personal judgement and that insufficient systematic documentation weakens formal risk-assessment practice [29]. These findings suggest a practice-oriented gap for methods that are transparent, interpretable, and based on data already generated during project delivery. The RCDM framework proposed in this paper therefore responds to this practical need by offering a more accessible way to introduce risk-informed duration planning in organizations with different levels of digital and analytical maturity.

The infrastructure context also matters for the transferability of duration-risk evidence. Water and wastewater infrastructure requires coordination between civil works, mechanical and electrical systems, public-law permitting, environmental requirements, local utilities, land and access constraints, and funding obligations [41,42]. The risk register used in this study was previously developed for EU co-financed water and wastewater infrastructure projects and contains 11 risk categories and 54 individual risks [43]. At the same time, broader infrastructure literature shows that many delay mechanisms are not sector-specific: public approvals, design changes, external stakeholders, physical conditions, site access, procurement documentation, and contract-execution issues appear across different types of public infrastructure [5,6,40,44]. This suggests that the numerical coefficients derived in one portfolio should be locally calibrated before direct use elsewhere, but the methodological logic can be transferred to other portfolios where comparable contract-amendment data are available.

Taken together, the reviewed studies provide strong but partial foundations for the present research. Delay studies explain why time overruns occur; extension-of-time and claim studies show how time impacts are documented and contractually recognized; change-order research demonstrates that contractual records can be analyzed empirically; and duration-estimation studies provide methods for modeling time uncertainty. What remains less developed is the operational bridge between these strands: a procedure that uses accepted amendment outcomes, their stated causes, and the original contractual time baseline to derive reusable duration allowances. The RCDM framework is positioned at that interface. It does not replace delay analysis, claim assessment, or duration-prediction models; rather, it converts formally recognized extension outcomes into comparable ratios and risk-time premiums that can be recalibrated across contract portfolios.

Table 1 shows that existing research provides the necessary building blocks, but usually treats them separately. The proposed framework is positioned as the operational link between those streams: it uses formally recognized extension outcomes as empirical observations and converts them into normalized duration ratios and risk-time premiums. This positioning establishes the methodological basis for the data structure and analytical procedure described in the following section.

Table 1. Positioning of the present study relative to prior literature.

Literature Stream	What Existing Studies Provide	Remaining Limitation	Contribution of This Study
Construction delays and schedule overruns	Identification, ranking, and classification of recurring delay causes [1–6]	Mainly explains why delays occur, but usually does not convert approved time-extension outcomes into duration multipliers	Uses documented extension outcomes as input for multiplier calibration
Extension-of-time claims and contract administration	Methods for delay analysis, claim assessment, entitlement evaluation, and contractual documentation [7–16]	Mainly retrospective and claim-oriented	Reuses formally approved extension records as empirical evidence for future planning
Change orders and amendments	Empirical analysis of change orders, causes, cost growth, schedule growth, and project performance [17–24]	Usually focuses on occurrence and impact rather than risk-specific duration coefficients	Decomposes extension-related amendments into risk-time premiums
Risk-based duration estimation	Simulation, fuzzy, statistical, machine-learning, and early-stage duration-prediction models [25–30,32–38]	Often relies on expert scoring, activity models, general project metadata, or predictive algorithms	Uses formal amendment records and documented materialized risks as calibration data
Infrastructure transferability	Evidence that permitting, design, site, stakeholder, and contract-execution risks recur across infrastructure portfolios [5,6,40,42,44]	Numerical effects are context-dependent and require local calibration	Provides a replicable framework that can be recalibrated in other infrastructure portfolios

3. Materials and Methods

3.1. Research Design and RCDM Framework

This study applies a quantitative, document-based research design to develop the RCDM framework. The starting point is a portfolio of signed works contracts and contract amendments that formally granted extensions of time. Rather than treating these

amendments only as administrative records, the study uses them as observed evidence that implementation risks affected contractual time performance.

The workflow links three data sources: contract-level information, amendment-level extension records, and a predefined risk register. The analysis proceeds by normalizing approved extensions against the initially contracted duration, assigning each extension to the documented risk cause or causes, applying impact-weighted attribution where several risks were recorded in one amendment, estimating risk-time coefficients, and assessing uncertainty and explanatory performance. Figure 1 summarizes this sequence and shows how raw contract records are converted into the analytical variables used in the subsequent steps. Portfolio learning and recalibration refers to the use of newly generated contract-amendment records to update the empirical basis of the framework and periodically recalibrate duration multipliers and risk-time coefficients for future comparable contracts.

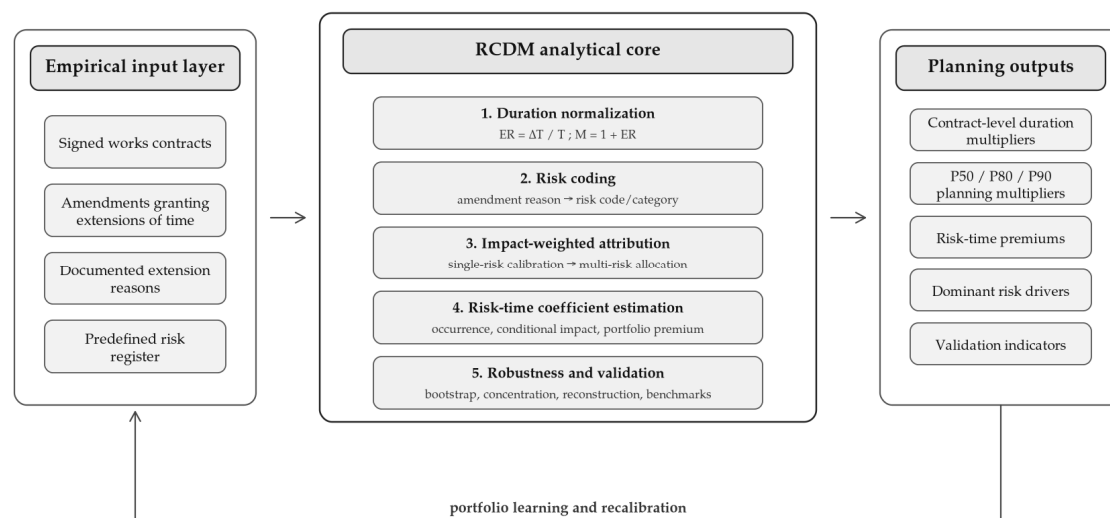


Figure 1. Risk-Calibrated Duration Multiplier (RCDM) framework.

Several statistical operations used in the framework—ratio calculation, bootstrap re-sampling, concentration measures, logistic regression, and generalized linear modeling—are established methods. They are used here as components of a single workflow rather than as standalone contributions. The methodological contribution lies in the way these procedures are combined with formal amendment documentation and risk coding, so that the same logic can be replicated on other contract portfolios where comparable records are available.

3.2. Empirical Context and Analytical Dataset

The empirical application was conducted on works contracts from a broader portfolio of 63 EU-funded water and wastewater infrastructure projects in Croatia. The total value of the portfolio was EUR 4,306,880,307.98, of which EUR 3,428,172,335.00 represented non-refundable grant funding. The portfolio represents a strategically significant public infrastructure program aimed at improving water supply, wastewater collection and treatment, environmental protection, service reliability, and compliance with EU water-sector requirements. Three projects were excluded from the contract-level dataset because no works contract had been signed by the analytical cut-off date. The grant agreement for one project had been terminated, while two projects were still in the planning stage and had not reached public procurement or contract signature. Consequently, no initially contracted duration, works-contract amendment, or duration multiplier could be defined for those projects.

The final analytical dataset comprised 197 signed works contracts from 60 projects. The works contracts included in the dataset were signed between 2014 and 2024. The analytical cut-off date was 31 December 2024, while the database was compiled in 2024 and 2025 through document-level review of contract documentation and contract amendments. The contracts were predominantly administered under FIDIC Red and Yellow Book conditions, with a smaller number of non-FIDIC works contracts. FIDIC Red Book contracts generally correspond to construct-only arrangements in which the Employer provides the design documentation, while FIDIC Yellow Book contracts correspond to design-build arrangements in which the Contractor assumes responsibility for design and construction [45,46]. The statistical unit of analysis was the works contract, not the EU project. This distinction is important because one EU-funded infrastructure project may contain several contracts, including works, supervision, equipment procurement, visibility, and other supporting contracts. This study focused exclusively on works contracts because they represent the central delivery mechanism for infrastructure implementation and are the contract type most directly associated with construction duration.

The database was structured into three connected components. The contract-level dataset contained one row per signed works contract and included project and contract identifiers, contract form, delivery model, primary infrastructure type, contract signing date, initially contracted duration, contract status at the cut-off date, number of amendments, number of time-extension amendments, total approved extension duration, final approved duration, extension ratio, and duration multiplier. The amendment-level dataset contained one row per amendment that resulted in a formal extension of time and included amendment identifier, amendment signing date, extension increment, documented reason for extension, and associated risk codes and categories. The third component was the adopted risk register, previously developed for EU co-financed water and wastewater infrastructure projects in Croatia [43]. The register contains 11 risk categories and 54 individual risks. Across all 197 signed works contracts, the amendment-level dataset contained 813 signed contract amendments, of which 386 granted formal extensions of time. These records describe the full portfolio of approved time extensions up to the cut-off date. The main duration-multiplier and risk-time coefficient calibration was based on the completed-contract subset, which included 337 extension-related amendments linked to 103 completed contracts with at least one approved extension of time.

3.3. Impact-Weighted Risk Attribution and Multiplier Decomposition

Each extension-related amendment was classified according to the adopted risk register. The register groups individual risks into 11 categories: Political, Financial and Economy, Social, Environment and Nature, Management and Organization, Public Procurement, Design, People and Logistics, Contract and Legal, Construction Site and Construction, and Physical Conditions [43]. The term “Political” should not be interpreted narrowly as daily political decision-making. In this study, the most relevant risk within that category is R.1.3, defined as delay of public-law bodies in procedures for issuing permits, decisions, approvals, or other administrative acts. The dominant mechanism captured by this category is therefore institutional and public-law procedural delay.

The amendment documentation stated the reasons for requested and approved extensions of time. However, where an amendment was associated with more than one risk, the documentation did not quantify the exact causal share of each risk in the approved extension duration. The proportional contribution of each risk in multi-risk amendments therefore could not be directly observed from the source records. For single-risk amendments, the full extension increment was assigned to the documented risk. For multi-risk amendments, a single-risk-calibrated impact-weighted rule was applied. This was

done to avoid assuming that all documented risks contributed equally to the approved extension duration.

Let T_{0i} denote the initially contracted duration of contract i , and ΔT_i the total formally approved extension of that contract, both expressed in months. The contract-level extension ratio was calculated as follows:

$$ER_i = \frac{\Delta T_i}{T_{0i}}, \quad (1)$$

and the duration multiplier was defined as follows:

$$M_i = 1 + ER_i = 1 + \frac{\Delta T_i}{T_{0i}}, \quad (2)$$

For contracts without formal extensions of time, $\Delta T_i = 0$, $ER_i = 0$, and $M_i = 1$. The main multiplier calibration was performed on completed contracts because their final approved duration was known at the analytical cut-off date. Ongoing contracts were retained for descriptive portfolio analysis, but not used as the primary basis for final multiplier calibration, since additional amendments could still occur after the cut-off date. Terminated contracts were also excluded from the primary calibration because their final approved duration may not represent completed delivery of the intended works. For each extension-related amendment j belonging to contract i , the addendum-level extension ratio was calculated as follows:

$$ER_{ij} = \frac{\Delta T_{ij}}{T_{0i}}, \quad (3)$$

where ΔT_{ij} is the extension increment approved by amendment j . This normalization made extensions comparable across contracts of different initial durations.

Risk contributions were aggregated by risk category and individual risk code. Single-risk amendments were assigned fully to one risk. For multi-risk attribution, weights were calibrated from amendments in which only one risk was documented. These records provide the clearest observable evidence of the time impact of individual risks because no allocation between multiple causes is required. To avoid over-representing contracts with several amendments for the same risk, calibration was performed at the contract-risk level. Let r denote an individual risk code, C_r the set of completed contracts in which risk r appeared in single-risk amendments, and S_{ir} the set of single-risk amendments attributed to risk r on contract i . The single-risk impact score was calculated as follows:

$$A_r = \frac{1}{|C_r|} \sum_{i \in C_r} \sum_{j \in S_{ir}} \frac{\Delta T_{ij}}{T_{0i}}. \quad (4)$$

For a multi-risk amendment with risk set K_{ij} , the allocation weight for risk r was then calculated as follows:

$$\omega_{ijr} = \frac{\tilde{A}_r}{\sum_{l \in K_{ij}} \tilde{A}_l}, \quad (5)$$

where A_r denotes the applicable calibration score for risk r . A three-level calibration hierarchy was applied. First, an individual risk-code score was used where at least three contract-level single-risk observations were available. Second, where the individual risk-code score was unavailable or based on fewer than three observations, the corresponding risk-category score was used. Third, where neither the risk-code nor the risk-category score was available, the global mean single-risk impact score was applied.

The risk-attributed extension months were calculated as follows:

$$\Delta T_{ijr}^{risk} = \omega_{ijr} \times \Delta T_{ij}, \quad (6)$$

and the corresponding risk-attributed extension ratio was calculated as follows:

$$ER_{ijr}^{risk} = \omega_{ijr} \times ER_{ij} = \omega_{ijr} \times \frac{\Delta T_{ij}}{T_{0i}}. \quad (7)$$

This procedure preserves the total approved extension duration of each amendment and avoids double counting. At the same time, it allows multi-risk amendments to reflect empirically observed single-risk time impacts rather than assuming equal contribution of all documented risks.

In the completed-contract sample used for final multiplier calibration, 337 extension-related amendments were recorded. Of these, 280 were single-risk records and 57 were multi-risk records. Among the multi-risk amendments, 47 included two risks and 10 included three risks. After expanding these multi-risk amendments to the risk-attribution level, the 57 amendments produced 124 multi-risk attribution rows. Of these rows, 106 were weighted using individual risk-code scores, 15 using risk-category fallback scores, and 3 using the global fallback score. The resulting risk-attributed extension months and ratios were then aggregated by individual risk code and risk category in the subsequent risk-time coefficient analysis.

By conducting these steps, approved extension increments were normalized and attributed to individual risk codes at the amendment level. The next step was to aggregate these amendment-level risk contributions to the contract and risk-category level. Let J_i denote the set of extension-related amendments belonging to contract i , let K_{ij} denote the set of individual risk codes associated with amendment j , and let R_g denote the set of individual risk codes belonging to risk category g . The risk-attributed extension ratio of category g on contract i was calculated as follows:

$$ER_{ig}^{risk} = \sum_{j \in J_i} \sum_{r \in K_{ij} \cap R_g} ER_{ijr}^{risk}. \quad (8)$$

This aggregation step links the impact-weighted amendment-level attribution to the contract-level multiplier structure. If a contract had no approved extension associated with category g , then $ER_{ig}^{risk} = 0$. The same aggregation logic was also applied at the individual risk-code level for descriptive ranking of dominant risks. For each risk category g , three quantities were calculated: occurrence rate, conditional mean risk extension ratio, and portfolio risk premium.

First, the occurrence rate π_g was defined as the proportion of completed contracts in which risk category g contributed to at least one extension of time:

$$\pi_g = \frac{n_g}{N}, \quad (9)$$

where n_g is the number of completed contracts with $ER_{ig}^{risk} > 0$, and N is the total number of completed contracts in the calibration sample.

Second, the conditional mean risk extension ratio θ_g was calculated as the average risk-attributed extension ratio among completed contracts in which risk category g occurred:

$$\theta_g = \frac{1}{n_g} \sum_{i: ER_{ig}^{risk} > 0} ER_{ig}^{risk}. \quad (10)$$

This coefficient represents the average proportional increase in contract duration associated with risk category g , conditional on that category being observed.

Third, the portfolio risk premium λ_g was calculated as follows:

$$\lambda_g = \pi_g \times \theta_g = \frac{1}{N} \sum_{i=1}^N ER_{ig}^{risk}. \quad (11)$$

The portfolio premium represents the average contribution of risk category g to the completed-contract duration multiplier across the full calibration sample, including contracts in which that category did not occur. This distinction is important because a risk category may have a high conditional impact when it occurs but a smaller portfolio contribution if it appears only rarely.

The completed-contract mean duration multiplier can therefore be decomposed into risk-category premiums as follows:

$$\bar{M} = 1 + \sum_{g=1}^G \lambda_g. \quad (12)$$

where G is the number of observed risk categories. This decomposition is central to the RCDM framework. It transforms the overall duration multiplier from a single portfolio average into interpretable risk-specific time premiums. In practical terms, it shows which categories of risk contribute most to the expected increase in contract duration and therefore where planning allowances and mitigation attention should be concentrated.

3.4. Statistical Validation and Uncertainty Assessment

The statistical assessment combined uncertainty estimation, concentration analysis, reconstruction validation, benchmark modeling, and outlier robustness checks. Bootstrap confidence intervals were estimated using 10,000 contract-level resamples with replacement [47]. Resampling was performed at the contract level rather than at the amendment level because multiple amendments may belong to the same contract, and treating amendments as independent observations would overstate the effective sample size. In each bootstrap iteration, completed contracts were resampled and the relevant statistics were recalculated. A fixed random seed of 2026 was used to ensure reproducibility of the reported confidence intervals. Bootstrap distributions were used to estimate confidence intervals for mean multipliers, percentile multipliers, total extension premiums, and risk-time premiums.

Percentile-based duration multipliers were calculated to provide risk-informed planning values. The P50 multiplier represents the median duration multiplier, while P80 and P90 represent more conservative planning factors. These percentiles allow duration planning to be expressed as a range of confidence levels rather than as a single deterministic value.

Risk-premium concentration was measured with concentration ratios. Let λ_g denote the portfolio premium of the risk category g , and $\lambda_{(g)}$ denote risk premiums sorted in descending order. The concentration ratio for the top q categories was calculated as follows:

$$CR_q = \frac{\sum_{g=1}^q \lambda_{(g)}}{\sum_{g=1}^G \lambda_g}, \quad (13)$$

The CR_2 and CR_5 indicators were used to assess whether the total extension premium was concentrated in a small number of dominant risk categories.

The share of each risk category in the total extension premium was calculated as follows:

$$s_g = \frac{\lambda_g}{\sum_{m=1}^G \lambda_m}. \quad (14)$$

The Herfindahl–Hirschman Index was then calculated as follows:

$$HHI = \sum_{g=1}^G s_g^2, \quad (15)$$

and the effective number of risk categories as follows:

$$N_{eff} = \frac{1}{HHI}. \quad (16)$$

This indicator expresses the concentration of the extension premium as the equivalent number of equally important categories.

A leave-one-contract-out reconstruction procedure was used to assess whether calibrated risk-time coefficients could reproduce observed contract-level extension ratios. For each completed contract i , that contract was temporarily excluded from the calibration dataset, and conditional mean risk-time coefficients were recalculated using the remaining contracts. The extension ratio of the excluded contract was reconstructed as follows:

$$ER_i^{(-i)} = \sum_{g \in G_i} \hat{\theta}_g^{(-i)}, \quad (17)$$

where G_i is the set of risk categories observed for contract i and $\hat{\theta}_g^{(-i)}$ is the conditional mean extension ratio for risk category g , estimated without contract i . For contracts without extensions, G_i was empty and the reconstructed extension ratio was zero. The reconstructed and observed extension ratios were compared using mean absolute error, root mean squared error, coefficient of determination, Pearson correlation, and Spearman rank correlation. Performance was benchmarked against a portfolio-mean predictor.

Two benchmark regression models were estimated for diagnostic comparison. Logistic regression was selected for extension occurrence because the dependent variable was binary, indicating whether a completed works contract received at least one approved extension of time [48]. A Gamma generalized linear model with a log link was selected for positive extension ratios because the dependent variable was continuous, strictly positive among extended contracts, right-skewed, and non-negative by definition [49]. The log link also allowed the estimated effects to be interpreted multiplicatively. These models were not intended to replace the risk-time coefficient framework; their role was to evaluate how much explanatory value could be obtained from general contract-profile variables. Candidate explanatory variables included contract form, initial contracted duration, and contract signing period. Infrastructure type and delivery model were considered but not retained in the final parsimonious models because of collinearity with contract form and/or sparse categories.

An additional Gamma generalized linear model was estimated to test whether risk categories significantly differentiated conditional risk-time impact. A likelihood-ratio test, Akaike Information Criterion improvement, and deviance reduction were used to evaluate the additional explanatory contribution of risk-category terms relative to a control model.

Finally, outlier robustness was assessed to determine whether reconstruction results were driven by a small number of extremely extended contracts. Outliers were defined using observed contract-level extension ratios, not model residuals. Two pre-specified trimming rules were used: the standard interquartile range rule and a P95 outcome-based trimming rule. This analysis was used only to assess the stability of correlation and error-reduction indicators under reduced influence of extreme duration outcomes.

Data processing and statistical analyses were performed in Python 3.13.5 using standard scientific Python libraries. Microsoft Excel was used for structured data entry and manual review of contract and amendment records.

4. Results

4.1. Analytical Sample and Duration-Multiplier Profile

As described in Section 3.2, the final contract-level dataset comprised 197 signed works contracts from 60 projects within the broader portfolio of 63 EU-funded water and wastewater infrastructure projects. Of the 197 signed works contracts, 125 received at least one formal extension of time, corresponding to an overall extension rate of 63.5%. At the analytical cut-off date, 149 contracts were completed, 41 were ongoing, and 7 were terminated. Table 2 summarizes the contract-status structure and the duration-multiplier profile of the analytical sample.

Table 2. Analytical sample, extension profile, and duration multipliers by contract-status sample.

Sample	<i>n</i>	With Extension	Extension Rate	Total Extension Months	Mean <i>M</i>	P50 <i>M</i>	P80 <i>M</i>	P90 <i>M</i>	Main Interpretation
All signed works contracts	197	125	63.5%	1721.884	1.338	1.191	1.590	1.848	Describes the full signed works-contract portfolio
Completed contracts	149	103	69.1%	1379.868	1.372	1.233	1.635	1.886	Main calibration sample for final multipliers
Ongoing contracts	41	20	48.8%	300.089	1.236	1.000	1.343	1.729	Descriptive only; final extensions may still increase
Terminated contracts	7	2	28.6%	41.926	1.212	1.000	1.127	1.625	Excluded from final calibration due to non-standard closure

For completed contracts, the mean duration multiplier was 1.372. This means that final approved durations were, on average, 37.2% longer than initially contracted durations. The median multiplier was 1.233, indicating that half of completed contracts had approved durations up to approximately 23.3% above their initial duration. The P80 and P90 multipliers were 1.635 and 1.886, respectively, showing that more conservative planning benchmarks would require substantially larger duration allowances than the portfolio mean.

Bootstrap uncertainty intervals confirmed that the completed-contract multiplier estimates were materially above 1.000. For all completed contracts, the 95% bootstrap confidence interval for the mean multiplier was 1.296–1.455. The corresponding intervals were 1.500–1.752 for P80 and 1.723–2.202 for P90. These intervals indicate that the main duration-multiplier estimates are not driven only by a small number of individual observations.

4.2. Contract Form Differences in Completed Contracts

Figure 2 presents the distribution of completed-contract duration multipliers by contract form. Completed FIDIC Red Book contracts showed higher duration multipliers than completed FIDIC Yellow Book contracts. For FIDIC Red contracts, the mean multiplier was 1.412, with P80 and P90 values of 1.713 and 2.069, respectively. For FIDIC Yellow contracts, the mean multiplier was 1.261, with P80 and P90 values of 1.370 and 1.547, respectively. The extension rate was similar in both groups, 70.8% for FIDIC Red and 67.6% for FIDIC Yellow, but the magnitude of approved duration extension was higher for FIDIC Red contracts. The non-FIDIC Other group is shown for completeness but is not interpreted separately because of the small number of contracts.

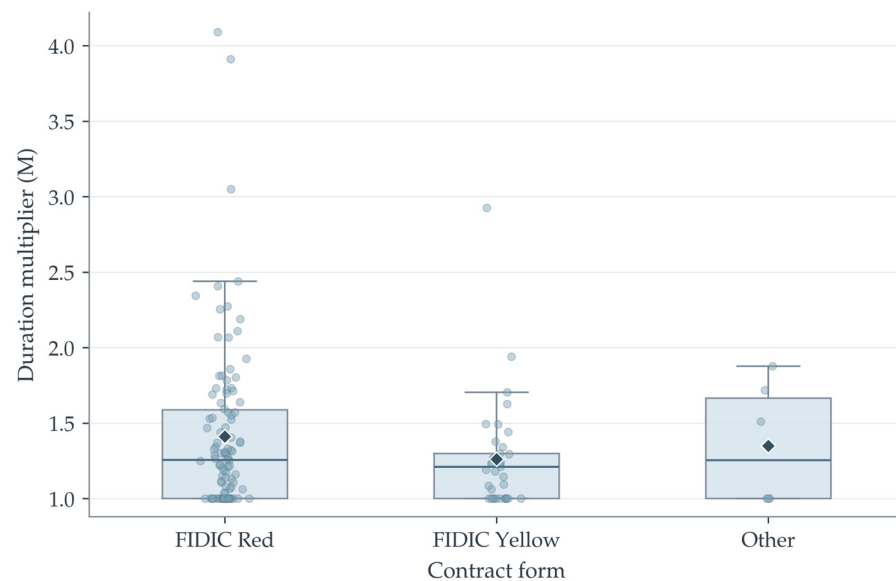


Figure 2. Completed-contract duration multipliers by contract form. Boxplots show the distribution within each contract-form group; circles represent individual contracts, and diamond markers indicate group means.

The difference between Red and Yellow Book contracts should not be interpreted as a universal performance ranking of contract forms. Rather, it reflects the risk-allocation and infrastructure-type structure of this portfolio. FIDIC Red Book contracts in the analyzed dataset were predominantly construct-only contracts, where design documentation was provided by the Employer. FIDIC Yellow Book contracts were generally design-build contracts, where the Contractor assumed responsibility for both design and execution. This contractual distinction is important for interpreting design-related extensions of time in the Discussion.

4.3. Risk-Time Premiums and Dominant Extension Drivers

The risk-attribution results were calculated using the single-risk-calibrated impact-weighted method described in Section 3.3. Multi-risk amendments were weighted according to empirically observed single-risk time impacts, while preserving the total approved extension duration of each amendment.

Figure 3 shows the portfolio risk premiums by risk category. The largest portfolio premium was associated with the Political category, especially risk R.1.3. The second largest premium was associated with Design risks. Together, Political/public-law procedural and Design risk categories accounted for 60.9% of the total completed-contract extension premium.

Table 3 provides the risk-time coefficient structure underlying this decomposition. The occurrence rate shows how often a risk category appeared in completed contracts, the conditional mean shows the average proportional extension when the category occurred, and the portfolio premium shows the average contribution of that category to the total duration multiplier across all completed contracts.

The decomposition shows that the completed-contract mean duration multiplier of 1.372 can be expressed as a base value of 1.000 plus an extension premium of approximately 0.372. Political/public-law procedural risks contributed 0.131 of this premium, while Design risks contributed 0.096. The top five categories—Political, Design, Environment and Nature, Physical Conditions, and Construction Site and Construction—accounted for 93.9% of the total extension premium. This indicates that approved time extensions were

not evenly distributed across the risk register; instead, they were concentrated in a limited set of dominant risk mechanisms.

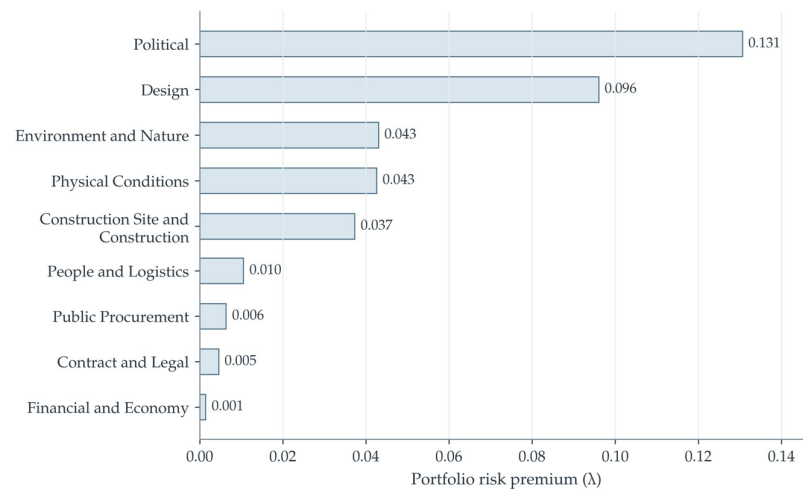


Figure 3. Portfolio risk premiums by risk category.

Table 3. Impact-weighted risk-time coefficients and portfolio risk premiums by risk category.

Risk Category	Contracts Affected	Occurrence Rate π	Conditional Mean θ	Portfolio Premium λ	Share of Total Premium	Allocated Months	Main Interpretation
Political	51	34.2%	0.382	0.131	35.1%	503.974	Largest contributor; mainly public-law procedural delay
Design	53	35.6%	0.270	0.096	25.8%	334.234	Second largest contributor; linked to design documentation quality
Environment and Nature	37	24.8%	0.173	0.043	11.6%	142.182	Frequent external/environmental contribution
Physical Conditions	19	12.8%	0.334	0.043	11.4%	142.290	Less frequent, but high conditional impact
Construction Site and Construction	33	22.1%	0.168	0.037	10.0%	143.323	Moderate occurrence and moderate impact
People and Logistics	13	8.7%	0.120	0.010	2.8%	38.855	Smaller formally recognized time premium
Public Procurement	1	0.7%	0.941	0.006	1.7%	48.930	High conditional value, but isolated occurrence
Contract and Legal	5	3.4%	0.136	0.005	1.2%	19.772	Low portfolio contribution
Financial and Economy	3	2.0%	0.069	0.001	0.4%	6.333	Minimal recognized time contribution in completed contracts

At the individual risk-code level, R.1.3 (Delay of public-law bodies in the procedures for making other permits and decisions) was the largest contributor, with a portfolio premium of 0.127 and 492.112 allocated months in completed contracts. R.7.1 (Insufficient quality and errors in project documentation) was the second largest, with a portfolio premium of 0.086 and 296.200 allocated months. Together, R.1.3 and R.7.1 accounted for approximately 57.4% of the total completed-contract extension premium. This confirms that the category-level dominance of Political and Design risks was driven primarily by public-law procedural delays and design-documentation issues.

4.4. Statistical Validation, Concentration, and Robustness of the RCDM Framework

The statistical validation assessed whether the RCDM framework produced stable and interpretable results, rather than only descriptive averages. Table 4 summarizes the main validation, concentration, and robustness indicators.

Table 4. Validation, concentration, and robustness indicators of the RCDM framework.

Assessment Area	Indicator	Result	Interpretation
Duration-multiplier uncertainty	Mean completed-contract multiplier	1.372	Completed contracts were on average 37.2% longer than initially contracted
Duration-multiplier uncertainty	95% bootstrap CI for mean M	1.296–1.455	Mean multiplier remained materially above 1.000 under resampling
Planning percentiles	P50/P80/P90 multipliers	1.233/1.635/1.886	Provides median, conservative, and high-conservatism planning benchmarks
Total extension premium	Mean extension premium	0.372	Average proportional extension beyond initial duration
Top-two concentration	Political + Design share	60.9%	Two categories explain more than half of the total extension premium
Top-two bootstrap stability	95% CI for top-two share	51.3–70.6%	Dominance of the top two categories remains stable in bootstrap resampling
Top-two dominance probability	Probability that top two exceed 50%	98.7%	Strong evidence that extension premium is concentrated
Top-five concentration	Top-five category share	93.9%	Most extension premium is concentrated in five categories
Portfolio concentration	HHI	0.227	Indicates moderate-to-high concentration of time premium
Effective number of categories	(N _{eff})	4.40	Although 11 categories exist, the time effect behaves like about four to five equally important categories
Reconstruction validation	Pearson correlation	0.564	Moderate linear association between observed and reconstructed extension ratios
Reconstruction validation	Spearman correlation	0.778	Strong rank-order agreement; the framework ranks extension severity well
Reconstruction validation	MAE	0.222	Average reconstruction error equals 22.2% of initially contracted duration
Reconstruction validation	RMSE	0.417	Larger errors remain for extreme extension outcomes
Benchmark comparison	MAE reduction vs. portfolio mean	35.5%	Risk-calibrated reconstruction improves substantially over a non-risk-adjusted benchmark
Benchmark comparison	RMSE reduction vs. portfolio mean	16.9%	Improvement remains when larger errors are penalized more strongly
Risk-category explanatory test	Gamma GLM likelihood-ratio test	($p < 0.001$)	Risk-category terms significantly improve explanation of conditional risk-time impact

The concentration indicators show that the extension premium was structurally concentrated. The Herfindahl–Hirschman Index was 0.227, corresponding to an effective number of 4.40 risk categories. This means that, although the adopted risk register contains 11 risk categories, the observed time-extension premium behaved as if it were concentrated in roughly four to five equally important categories. In 98.7% of bootstrap resamples, the two leading categories accounted for more than 50% of the total extension premium.

The leave-one-contract-out reconstruction procedure tested whether risk-time coefficients calibrated on all other completed contracts could reproduce the observed extension ratio of the excluded contract. The reconstruction achieved a Pearson correlation of 0.564 and a Spearman rank correlation of 0.778 with observed extension ratios. The Spearman result is particularly relevant for planning because it indicates that the framework

was effective in ranking contracts according to relative extension severity, even if exact month-by-month prediction remains uncertain.

Figure 4 compares observed and reconstructed extension ratios. The scatter pattern shows that the framework captures the general ordering of low, medium, and high extension cases, while larger deviations remain for a limited number of extreme contracts. This is consistent with the difference between the stronger Spearman correlation and the lower Pearson correlation.

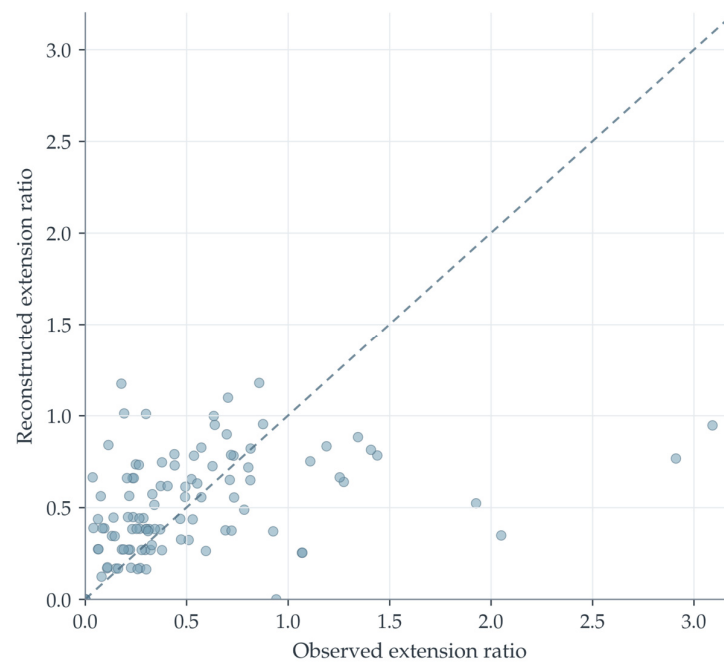


Figure 4. Observed versus reconstructed extension ratios using leave-one-contract-out validation. Points represent completed contracts, and the dashed diagonal line represents the 1:1 reference line, where observed and reconstructed extension ratios are equal.

Outlier robustness checks confirmed that the main validation pattern was not driven solely by extreme contracts. Under the interquartile-range trimming rule, the Pearson correlation increased to 0.643, while Spearman correlation remained stable at 0.774. Under the P95 trimming rule, Pearson correlation increased to 0.647, with Spearman correlation again remaining stable at 0.774. These results suggest that extreme duration outcomes increase absolute error, but do not undermine the basic risk-time ranking structure of the framework.

Overall, the Results show that approved extensions of time can be transformed into a stable and interpretable duration-multiplier structure. The completed-contract multiplier profile provides empirical planning factors, the impact-weighted risk decomposition identifies the main contributors to extension time, and the validation results show that risk-time coefficients improve reconstruction compared with a non-risk-adjusted portfolio-mean benchmark.

5. Discussion

5.1. From Deterministic Contract Duration to Risk-Calibrated Time Governance

The results support the central premise of this study: initially contracted duration should not be treated only as a technical scheduling parameter. In public infrastructure programs, contract duration is also a governance commitment. It is linked to procurement preparation, funding eligibility, program indicators, public-service delivery, administrative approvals, and institutional accountability. This is consistent with project-management and

infrastructure literature showing that time and cost deviations are recurrent in major public projects and that early planning is exposed to optimism bias, strategic misrepresentation, planning fallacy, and base-rate neglect [22,39,40,50,51].

The completed-contract mean multiplier of 1.372 should therefore not be interpreted as a recommendation that future contracts should automatically be extended by 37.2%. Its managerial meaning is different. It shows that the gap between initially contracted and formally approved duration is large enough to justify an explicit duration-risk allowance during procurement preparation. In other words, deterministic contract duration may remain necessary for tendering and contract administration, but it should be complemented by a risk-calibrated planning layer. The percentile multipliers are especially useful for this purpose. The P50 multiplier provides a median empirical benchmark, while P80 and P90 represent more conservative planning positions. These values should be understood as decision-support parameters, not as mechanical contingencies. For example, a P50 duration may be sufficient for routine planning scenarios, while P80 may be more appropriate where delay would affect EU funding deadlines, program indicators, service-delivery commitments, or environmental compliance obligations. P90 may be relevant for strategically critical contracts or contracts with high permitting, design, site, or interface uncertainty. This interpretation is consistent with probabilistic schedule-risk approaches, where uncertainty is expressed through ranges and confidence levels rather than a single deterministic estimate [26,32,33].

The managerial implication is that contracting authorities should distinguish between the contractual duration written into the tender documents and the risk-calibrated duration expectation used internally for program planning. The first is a legal and procurement instrument; the second is a management and governance instrument. When these two values are treated as identical, later extensions of time may appear as isolated contract problems. When they are separated, the organization can use historical evidence to anticipate schedule pressure, justify contingency, and prioritize risk mitigation before procurement.

5.2. Dominant Risk Drivers as Managerial Control Points

The impact-weighted results show that public-law procedural and design-related risks accounted for 60.9% of the total completed-contract extension premium. This does not mean that other risks are unimportant. Rather, it means that time-extension governance in this portfolio should focus first on the two risk mechanisms that consistently produced the largest formal duration effects: public-law procedural readiness and design readiness.

The Political category mostly refers to risk R.1.3: delay of public-law bodies in procedures for permits, decisions, approvals, and other administrative acts. Such procedures include location permits, construction permits, use permits, amendments to permits, special conditions, approvals, decisions, and similar acts required from public-law bodies. These interfaces are often outside the full control of both employer and contractor, yet they can materially affect the contractual time for completion. This finding is aligned with infrastructure-delay literature identifying statutory approvals, external stakeholders, public authorities, and institutional interfaces as recurrent sources of delay in public infrastructure delivery [5,6,44]. For contracting authorities, this result points to a concrete managerial control point: permitting-readiness should become a schedule-management gate before tendering. Such a gate does not require that every administrative risk be eliminated, which may be impossible. It requires that pending permits, approvals, land-access constraints, public-law conditions, and authority interfaces are explicitly listed, assigned to responsible owners, tracked centrally, and reflected in the tender-duration logic. For EU-funded or strategic public infrastructure projects, this also supports the use of escalation mechanisms, early coordination with public-law bodies, and structured monitoring of approval status.

Similar response strategies—regular communication with public-law bodies, reminders to authorities, and prioritization of permits for strategic or EU co-financed projects—were also identified in the previous risk-response study based on the same infrastructure context [43].

The Design category represents the second major control point. Its dominant individual risk, R.7.1, relates to insufficient quality and errors in project documentation. This finding is consistent with delay, change-order, and design-error literature, where incomplete design, errors, poor documentation, rework, and design changes are repeatedly linked to claims, variations, time overruns, and cost growth [1–4,6,17–20,22,52,53]. The contribution of the present study is to quantify that design risk in formal contract-duration terms. Design risk is not only a qualitative source of delay; in this portfolio it was one of the two largest contributors to the duration multiplier. The managerial implication is that design-readiness should be treated as a schedule-risk control, not only as a technical quality issue. Before tendering, employers should consider design-readiness reviews, constructability checks, bill-of-quantities consistency checks, clearer employer's requirements, and, where feasible, BIM-supported quantity and model checking [52–54]. In FIDIC Red Book contracts, where the employer generally provides the design, these controls are particularly important because design defects may later become employer-side grounds for extensions of time. In FIDIC Yellow Book contracts, design responsibility is shifted more strongly to the contractor, but employer's requirements and permitting assumptions still define the baseline from which later claims and amendments may arise [14,15,45,46,55].

Other risk groups should not be ignored. Environment and Nature, Physical Conditions, and Construction Site and Construction also contributed meaningfully to extension time. Weather, low temperatures, rainfall, snow, ice, groundwater, geotechnical uncertainty, unknown utilities, archaeological constraints, physical obstacles, and site-access conditions cannot always be eliminated before tendering. However, they can be managed through risk-proportionate investigation. Additional geotechnical, utility, archaeological, and site-readiness investigations may reduce later time risk, but they also require time and budget before procurement. The appropriate managerial response is therefore not to maximize pre-tender investigation in every case, but to target it where site conditions, linear routes, underground works, utility congestion, groundwater, or sensitive locations make the expected time benefit plausible [40,44,56,57].

People and Logistics had a smaller formally recognized time premium than general delay literature might suggest. This should not be interpreted as evidence that labor, equipment, material availability, or contractor capacity are irrelevant. It more likely reflects how risks become visible in formal extension-of-time documentation. Contractor-specific weaknesses, weak organization, insufficient manpower, or poor documentation management may be less likely to appear as accepted reasons for extension because they weaken the contractor's position in claim administration. Broader labor and material shortages may become recognized only when they are external, systemic, or market-wide. This distinction is consistent with construction-delay literature that identifies labor, materials, equipment, contractor capacity, and management issues as recurrent causes of delay [2,3,5,6,27,28]. For managers, the lesson is that amendment data are powerful, but they reflect formally accepted extension reasons, not every operational weakness experienced during delivery.

5.3. Contract Form, Risk Ownership, and Documentation Behavior

The difference between FIDIC Red and Yellow Book contracts should be interpreted through risk ownership rather than as a simple ranking of contract forms. In the analyzed portfolio, completed FIDIC Red Book contracts had higher duration multipliers than completed FIDIC Yellow Book contracts. This is consistent with the allocation of design responsibility: under Red Book conditions, the employer generally provides the design

documentation, while under Yellow Book conditions the contractor assumes responsibility for both design and construction [45,46]. This contractual distinction changes what can become a formally recognized ground for extension. In Red Book contracts, errors, omissions, or insufficient quality of employer-provided design documentation may support extensions of time because the contractor is not responsible for the original design. In Yellow Book contracts, the contractor's design responsibility reduces the possibility of relying on poor design documentation as an employer-side extension cause. This does not mean that Yellow Book contracts are inherently less risky. Rather, the risk is allocated and documented differently. Employer-driven changes, unclear employer's requirements, permitting assumptions, additional requirements, and interface issues may still generate extensions under design-build arrangements [11,12,14,15,45,46,55].

The Red–Yellow distinction is also intertwined with infrastructure type. In this portfolio, Red Book contracts were predominantly associated with network works, while Yellow Book contracts were generally associated with wastewater treatment plants, sludge-treatment facilities, or water-conditioning facilities. Network works are linear and spatially distributed, with greater exposure to access, traffic, utilities, property interfaces, field conditions, and geographically dispersed permits. Plant-type contracts have a different risk structure, often involving process technology, mechanical and electrical interfaces, equipment integration, performance requirements, and design-build responsibility. Prior design-build infrastructure research also shows that contract form and project type influence change orders, schedule performance, and the distribution of responsibility for changes [20,23,24].

The practical implication is that contract form should not be used as a standalone predictor of time-extension risk. A contracting authority should instead ask: which risks are owned by whom, which risks are visible in the contract baseline, and which risks can later become accepted grounds for extension? The RCDM framework supports this interpretation because it does not only compare Red and Yellow contracts; it decomposes approved extensions into risk mechanisms and therefore helps explain why contract-form differences appear.

5.4. RCDM as a Portfolio Learning and Contract-Governance Tool

The most important managerial implication of this study is that the RCDM framework can be used as a portfolio learning system, not only as a statistical model. Each approved extension of time contains information about a risk that became sufficiently important to affect contractual duration. If that information is coded consistently, it can support future procurement planning, schedule-contingency policy, portfolio risk registers, and program-level decision making. This shifts extension records from a retrospective claim-administration role toward a prospective governance role. Claims and extension-of-time literature already emphasizes documentation, traceability, contractual procedure, and consistent substantiation [7–13,16]. The present framework extends that logic: if a claim or amendment record is already documented for contract administration, it can also become a data point for future planning. The same record can therefore serve two purposes: it supports the contractual decision in the current project and improves the empirical evidence base for the next procurement cycle.

Figure 5 illustrates this governance logic. The cycle starts with risk-coded extension-of-time amendments, which feed a portfolio contract database. Periodic RCDM recalibration updates the empirical duration multipliers and risk-time coefficients. These outputs then inform procurement planning benchmarks, readiness gates, and risk actions. New contract delivery generates new amendment records, which again update the database. The key

managerial value is not only the calculation of one multiplier, but the creation of a repeatable organizational routine.

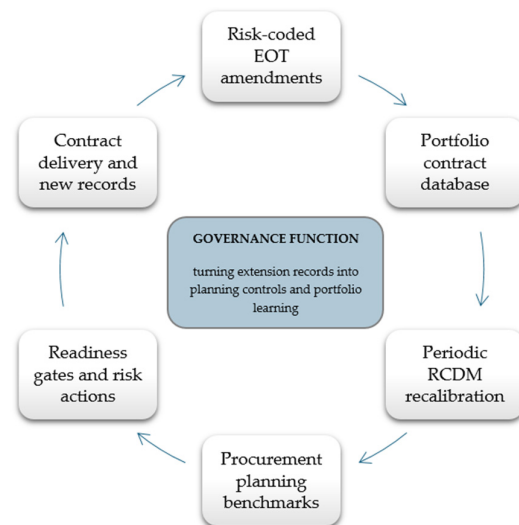


Figure 5. RCDM as a portfolio learning and contract-governance tool.

In practical terms, this requires relatively modest but disciplined changes in contract administration. Each extension request or amendment should include a standardized risk code from an adopted risk taxonomy. Where several risks are involved, all relevant risks should be recorded, not only a narrative explanation. The portfolio database should store initially contracted duration, approved extension duration, amendment date, extension reason, risk code, risk category, contract form, and completion status. Once a sufficient number of completed contracts is available, multipliers and risk-time premiums can be recalibrated periodically.

This is especially relevant for public-sector organizations that may not yet have highly mature digital project-management offices or advanced simulation platforms. Prior research on construction risk assessment has shown that implementation of advanced methods can be constrained by data availability, modeling expertise, organizational support, and risk-management maturity [29,31]. The RCDM framework addresses part of this implementation gap by using contract-administration records that organizations already generate. It is not intended to replace advanced simulation, machine-learning, or probabilistic schedule-risk models. Rather, it provides a transparent and accessible layer of empirical calibration that can be implemented early and further developed as digital and analytical capacities mature [26–31,34]. The validation results support this managerial use. The framework is more useful for risk-informed ranking and planning than for exact deterministic prediction of each contract’s final duration. The strong Spearman correlation indicates that the model is effective in distinguishing contracts with lower and higher extension severity. For practitioners, this is highly relevant: procurement and portfolio managers often need to know which future contracts require stronger readiness checks, larger time allowances, or more intensive monitoring, even if exact extension duration cannot be predicted perfectly.

5.5. Transferability, Limitations, and Future Research

The transferability of the study should be understood at two levels. The methodological logic is transferable, but the numerical coefficients are context-specific. The empirical coefficients reported in this paper were calibrated on EU-funded water and wastewater infrastructure works contracts in Croatia. They should therefore not be treated as universal constants for all countries, sectors, or contract types. However, the procedure can be applied wherever four types of data are available: initially contracted duration, approved extension duration, amendment date, and completion status.

sion duration, formal contract-amendment records, and documented causes of extension classified through a consistent risk taxonomy.

The most direct transferability is to comparable EU-funded public infrastructure portfolios, especially water and wastewater program implemented under public procurement, grant financing, multi-authority permitting, and standard-form or FIDIC-based contracts. The policy relevance of this sector extends beyond Croatia. Urban wastewater collection and treatment remain central to environmental and public-health objectives in the EU context [42]. Therefore, comparable water and wastewater programs in EU and neighboring countries may use the Croatian coefficients as empirical benchmarks, provided that local recalibration is performed where sufficient contract-amendment records exist.

The method may also be relevant beyond water and wastewater. Transport, energy, flood-protection, and public-building infrastructure often face similar mechanisms: permitting delays, design readiness, physical conditions, access constraints, stakeholder interfaces, weather exposure, procurement-documentation issues, and contract-execution complexity [5,6,40,44]. Nevertheless, the magnitude of risk-time premiums may differ substantially across sectors. For example, transport corridors may have stronger land-access and utility-interface exposure, while energy or treatment-plant projects may have stronger technology and equipment-interface risks. Therefore, the safest transferability claim is when the framework is broadly transferable, while coefficients should be locally calibrated.

The study also has boundaries that should be explicit. First, its practical application shown in this study focuses on one infrastructure sector, one country, and one EU-funded public portfolio. These boundaries define the calibration context. Second, the model measures formal works-contract duration extensions, not total project delay from feasibility study to final completion. Pre-contract procurement delay is outside the dependent variable unless it later affects the signed works contract through formal amendments. This distinction is important because public procurement decisions may be delayed by organizational factors, contract complexity, procedural choices, and institutional decision-making arrangements [58]. This should be seen as a boundary of the study's scope, not a weakness, because the purpose is to estimate duration multipliers for initially contracted works duration. Third, the analysis relies on formally approved extensions of time and on the quality of documented extension reasons. In the studied context, delays that affect the contractual time for completion must be formalized through amendments, which supports the reliability of the records. For future applications, a standardized amendment-coding protocol would further support comparability across portfolios and facilitate periodic recalibration of the framework.

Future research can develop the framework in several directions. First, researchers should apply the RCDM framework to other infrastructure sectors, including transport, energy, flood protection, public buildings, and rail or road infrastructure. This would test whether public-law procedural and design-related risks remain dominant elsewhere or whether sector-specific risk-time structures emerge. Second, cross-country studies should compare coefficients across EU and neighboring contexts with different administrative density, permitting systems, procurement rules, and contract-management practices. Third, future applications can further operationalize the framework during procurement preparation by combining calibrated historical multipliers with pre-contract risk-readiness reviews. In such use, P50, P80, and P90 multipliers would not be treated as fixed predictions, but as planning benchmarks selected according to the expected exposure of a future contract to permitting, design, site, market, and interface risks. As new contracts are delivered, their amendment records can then be added to the portfolio database and used for periodic recalibration. Fourth, the framework should be extended from time to combined cost-duration risk premiums by integrating extension-of-time amendments with financial amendments,

price-adjustment records, and payment data. Fifth, future studies could explore semi-automated risk coding of extension reasons using, e.g., natural-language processing, while preserving human validation for contractual interpretation. Finally, larger multi-country datasets would allow for hierarchical, Bayesian, or machine-learning extensions of the framework, while retaining the interpretability of risk-time premiums.

Overall, the results support the argument that contract-amendment records can become a practical evidence base for duration governance. The value of the RCDM framework is not only that it quantifies historical extensions. Its value is that it identifies dominant risk mechanisms, links them to procurement and contract-management decisions, and creates a repeatable process for updating planning assumptions as new contract evidence becomes available.

6. Conclusions

This study developed and demonstrated the Risk-Calibrated Duration Multiplier (RCDM) framework, a document-based method for converting formal time-extension amendments into empirical duration-planning parameters. The main conclusion is that approved contract amendments can be used not only as retrospective contract-administration records, but also as evidence of materialized risk that supports more realistic planning of future works-contract duration.

Applied to 197 signed works contracts from 60 EU-funded water and wastewater infrastructure projects in Croatia, the framework showed that completed contracts had a mean duration multiplier of 1.372, with P50, P80, and P90 values of 1.233, 1.635, and 1.886. After impact-weighted risk attribution, public-law procedural and design-related risk categories accounted for 60.9% of the total extension premium. The leave-one-contract-out reconstruction reduced mean absolute error by 35.5% relative to a portfolio-mean benchmark, indicating that the risk-calibrated structure provides more explanatory value than a non-risk-adjusted average.

For practice, the framework provides interpretable multipliers and risk-time premiums that can support tender-duration setting, schedule-contingency decisions, permitting-readiness and design-readiness checks, and portfolio learning through periodic recalibration. The numerical coefficients should be recalibrated before use in other sectors or jurisdictions, and the methodological logic is transferable wherever initially contracted duration, approved extensions of time, amendment records, and consistently coded extension causes are available. The wider value of the RCDM framework is that it turns records of past extensions into a portfolio learning and contract-governance tool: each closed contract improves the evidence base for planning the next one.

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Pro for the purposes of language refinement and polishing. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: Author Mariela Knezevic was employed by Croatian waters (Hrvatske vode), and Domagoj Knezevic was employed by Primakon d.o.o. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Meaning
APC	Article processing charge
BIM	Building Information Modeling
EU	European Union
EUR	Euro (currency)
FIDIC	Fédération Internationale des Ingénieurs-Conseils
GLM	Generalized linear model
HHI	Herfindahl–Hirschman Index
MAE	Mean absolute error
P50	50th percentile
P80	80th percentile
P90	90th percentile
RCDM	Risk-Calibrated Duration Multiplier
RMSE	Root mean squared error
RQ	Research question

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