A cost estimate method for bridge superstructures using regression analysis and bootstrap

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PRELIMINARY COST ESTIMATES RELY ON THE CONCEPTUAL DESIGN OF THE PROJECT AND USE ONLY BASIC DESIGN TECHNOLOGIES. Although they present the lowest expected accuracy, they are often used by key people involved in the construction process, thus playing a significant role. Bridge construction has increased over the last years, often exhibiting substantial overruns above estimated costs. To overcome this problem, it is crucial for the decision makers to have an early estimate of the final cost based on previous experience. This paper addresses the need for easy-to-use and reliable cost estimates during the early stages of projects for bridge superstructures, presenting a major impact on the total bridge construction cost. It proposes a conceptual cost estimate method that involves the estimation of both the material quantities and the relevant costs. It describes the development of prediction models for the material quantities of concrete and reinforcing and prestressing steel for three major bridge deck construction methods using regression analysis, while a bootstrap resampling method is used to produce estimate ranges. The material estimating models rely on the development of a database after collecting actual data from a large sample of modern bridges. The major assumptions underlying the correct application of the regression methodology were tested, and necessary adjustments were made. The proposed conceptual cost-estimating methodology uses information known before detailed plans are developed to provide fast and reliable results that can be very useful in the early stages of a road project.

Keywords
construction costs; bridges; estimation; regression analysis; bootstrap

INTRODUCTION

Every construction project evolves through a series of stages, originating from the preliminary study followed by several design stages and finally the implementation of the design with the actual construction. Cost estimates are produced throughout the life of a construction project and are used for different purposes depending on the available information and their expected accuracy.

Preliminary cost estimates, also referred to as pre-design cost estimates, feasibility estimates, or screening estimates (Ritz, 2004), are made before the project's detailed plans and specifications are known. According to Hendrickson (2008), a preliminary cost estimate relies on the conceptual design of the project and uses only the basic technologies for the design. Although preliminary cost estimates present the lowest expected accuracy, due to the limited available information, they are often used by key people involved in the construction process, including project owners, designers, contractors, and lending institutions. They are used for feasibility and budgeting purposes, the comparison and financial evaluation of alternative projects, and the application of appropriate financing procedures. As such, easy-to-use, inexpensive, and reasonably accurate methods for preliminary cost estimating are needed, especially for large-scale transport infrastructure projects that have traditionally exhibited substantial overruns above estimated costs by as much as 50% to 100% in most cases (Skamris and Flyvbjerg, 1997).

Modern motorways play a major role in the transportation infrastructure. The need to have environmentally friendly designs for motorways that overcome difficult geological terrains and bypass city centers or archaeological sites increases the necessity to construct bridges. Bridge construction often results in cost overruns. To overcome this problem, it is crucial for decision makers to have an early estimate of the final cost based on previous experience.

Comparative studies on the transportation infrastructure are rare, mainly because of the lack of large, reliable, and homogeneous databases. This is due to the reluctance of public clients to supply financial information regarding constructed projects, thereby making research in this domain difficult.

The superstructure presents a significant impact on the construction cost of a modern concrete bridge. According to Konstantinidis and Maravas (2003), its cost ranges from 35% to 53% of the total bridge construction cost, depending on the construction method used and the design system. Consequently, analytical models for conceptual cost estimating appear to be necessary.

This paper addresses the need for easy-to-use and reliable cost estimates for bridge superstructures during the early stages of a project and proposes a conceptual cost estimate method that relies on information known before the detailed plans and specifications are identified. Prediction models for the material quantities of concrete as well as reinforcing and prestressing steel for three major bridge deck construction methods are developed with the use of regression analysis, while a bootstrap resampling method is used to produce estimate ranges. The data used have been collected from the bridges of the 680-km long Egnatia Motorway traversing northern Greece.

Previous relevant cost studies and research

When reviewing the previous research on cost estimating for motorway bridges, it becomes evident that relevant cost studies fall into two categories. Most research efforts perform computer-intensive theoretical resolutions in order to optimize the final design from both technical and economic viewpoints through a trial-and-error process. On the other hand, very few studies rely on actual structural and economic data collected from constructed bridges in order to produce material and cost estimates.

Aparicio et al. (1996) developed a computer-aided design system for prestressed concrete highway bridges. The software package performs the complete design and produces the geometry and cost of all bridge elements. Previous efforts to create similar expert systems were made by Philbey et al. (1993) and Miles and Moore (1991).

Several research studies performed in the US also address the design optimization of prestressed concrete road bridges and rely on theoretical resolutions in order to minimize the construction cost of the bridge superstructure. Sirca and Adeli (2005) developed an optimization method for the superstructure cost of precast, prestressed concrete I-beam bridge systems, while Cohn and Lounis (1994) developed a three-level cost optimization approach for the optimal superstructure design of concrete motorway bridges. Lounis and Cohn (1993) proposed a method for the selection of the most economical girder type, optimal girder spacing, optimal prestressing force, and minimum superstructure cost per unit deck area for bridges consisting of precast prestressed girders with reinforced concrete slab. Sarma and Adeli (1998) provided a review of articles pertaining to cost optimization of concrete bridges. The aforementioned research studies provide preliminary cost and design estimates for concrete bridge superstructures conforming to American or Canadian specifications and for standard shapes and cross sections.

Meanwhile, Menn (1990) investigated the economy of prestressed concrete bridges relying on actual cost data and using a sample of 19 motorway bridges built in Switzerland between 1958 and 1985. Menn broke down the average construction costs into mobilization, substructure, superstructure, and accessories, concluding that these factors' contribution to the total bridge construction cost is 8.00%, 23.50%, 54.50%, and 14.00%, respectively. He argued that, although the sample represents a wide variety of conditions, the most important cost factors do not vary significantly from one bridge to another; consequently, the proposed breakdown of average construction costs can be very useful in preparing preliminary cost estimates. Menn also developed empirical equations for the quantities of concrete, reinforcing steel and prestressing steel in the bridge superstructure and proposed different equations for incrementally launched and balanced cantilever bridge construction.

In summary, research studies for motorway bridges using actual structural and cost data are very limited due to the lack of available information and the difficulty involved in developing large and reliable databases. Although cost estimates based on computer-aided resolutions can provide helpful insights, they fail to address structural changes that take place during the project's construction.

Concrete bridges of the Egnatia Motorway

The Egnatia Motorway is a recently constructed 680-km long modern motorway that constitutes part of the Trans-European Network for Transport. Its bridges represent approximately 16% of the total construction cost of the motorway. The largest overall bridge length exceeds 1,000 m while the largest maximum span reaches 235 m.

Each carriageway is carried by a separate bridge having a total width varying from 10.00 m to 17.75 m. The bridge decks can be categorized into one of three types: simply supported precast prestressed beams with composite slab, voided slab, or post-tensioned continuous box girder. The three major construction methods used are precast beams placed by launching beam or crane, cast-in-situ, and balanced cantilever. Advance shoring and incremental launching have also been used.

Egnatia Odos S.A. (EOAE) managed the motorway and administered its design, construction, operation, maintenance, and exploitation. The design of bridges was carried out by Greek or international structural design offices following an international competition. Each individual bridge design was first checked by an independent consultant office and then reviewed by EOAE's design department prior to construction. In addition, each study was also reviewed by the construction manager commissioned by EOAE with regard to the adaptation to local conditions, the constructability of the structure, and any special site conditions. In accordance with the current Greek legislation, the design of bridges was executed according to the German DIN standards. For earthquake loading, the Greek Seismic Regulation for Design of Bridges (E39/99) combined with the Greek Standard for Design of Earthquake Resistant Structures (EAK 2000) was utilized.

Data collection and database development

The proposed pre-design cost estimate method for bridge superstructures relies on the development of a database for modern concrete motorway bridges. A structured general questionnaire that includes all bridge sections from the foundations up to the superstructure and covers different designs and construction systems was developed. It includes actual structural information for the bridge (e.g., the quantities of concrete and reinforcing and prestressing steel), fundamental design parameters (e.g., length of spans, height of piers and abutments), and construction costs and time. The questionnaire was initially sent to the construction managers and the contractors' civil engineers. The authors visited the construction sites in order to scrutinize the completed questionnaires, confirm the validity of the provided data, and fill in missing information. Furthermore, they conducted several interview sessions with bridge experts, academics, and designers in order to improve their understanding of bridge design.

The current bridge database includes complete data from 68 structures: 31 bridges with simply supported precast prestressed beams with composite slab, 22 bridges with cast-in-situ decks, and 15 bridges with cantilever construction. The respective Table in Appendix A includes a representative sample of 19 bridges from the database. The database represents the final construction and includes all changes that took place during the implementation phase due to unforeseen site conditions. The actual structural data and material quantities, which in many cases were different from those determined during the design stages, were recorded.

Proposed method for pre-design cost estimates

The proposed cost estimate method involves two stages: the estimation of the superstructure's material quantities and the calculation of the relevant construction costs. The first stage is based on estimating models derived from the statistical processing of the collected data. Data input from the user include the number of spans or cantilevers, the length of each span or cantilever, the width of the deck, and the deck construction method. The proper estimating models are applied to extract the material quantities. The required input data consist of basic parameters known during the pre-design stages of the project. Based on contour maps and the alignment and specifications of the motorway under evaluation, the user calculates the length and width of the bridge and the length of the spans.

The second stage requires the unit prices for concrete (c_c), prestressing steel (c_p), and reinforcing steel (c_s) as data input. The relevant construction costs (C_c, C_p and C_s, respectively) are derived by multiplying the estimated material quantities with the item prices. The intended purpose of the cost estimate according to the various users substantially influences the applied unit prices. For example, the project owner can use the official tender unit prices determined by the government and derive the cost for budgeting purposes or for feasibility decisions. Meanwhile, the contractor can apply unit prices based on cost data from previous projects. The model also provides parametric estimate ranges for the total superstructure cost (*TC*).

Regression analysis

A parametric cost-estimating model consists of one or more functions or relationships between the cost as the dependent variable and the cost-governing factors as the independent variables. Regression analysis (RA) represents one of the most widely used methods for parametric cost estimation during early project stages. Traditionally, cost-estimating relationships are developed by applying RA to historical project information. The major advantages of RA lie in the simplicity in its use, the level of accuracy provided, and the parsimonious use of parameters. Its major drawbacks are the requirement for a defined mathematical form that best fits the available historical data, the difficulty in accounting for the large number of variables present in a construction project, and the numerous interactions among them (Hegazy and Ayed, 1998). Recent applications of RA for cost estimating can be found in Lowe et al. (2006) and Sonmez (2008).

A linear model was considered for regression modeling in this study. The approach used in the analysis includes a statistical hypothesis test to determine the significance of each independent variable coupled with the check of the rationality of the cause-and-effect relationships. This approach is consistent with the suggestions of Brubaker and McCuen (1990). The p-value, used to determine the statistical significance, denotes the probability that a regression coefficient equals zero and that the variable has no effect. In addition, regression coefficients were checked for theoretical accuracy, which should reflect the effect of the independent variables on the material quantities of the bridge superstructure.

The adjusted coefficient of determination (R^2) and the F-value were used to examine the goodness of fit of the model. R^2 provides a measure of the variability explained by the model, while the F-value tests the hypothesis that the coefficient of determination is zero. The significance of the F-test is the probability that the aforementioned hypothesis is correct.

The situation where the independent variables of regression modeling are highly intercorrelated is referred to as multicollinearity. Multicollinearity makes it difficult for researchers to correctly assess the marginal contribution of the variables (Belshey et al., 1980) as it causes large standard errors of the regression coefficients and leads to deceptive results in terms of statistical significance, hypothesis testing, estimation, and forecasting; The Pearson product-moment correlation coefficients were calculated in order to check the independent variables for multicollinearity before being used in the initial regression.

Model development

The design of a bridge superstructure is generally affected by many variables, such as the seismic design parameters, the alignment of the bridge, the construction sequence, the arrangement of longitudinal prestressing, the deck width, the arrangement and use of expansion joints in the deck, and the length of the span supported by the piers (Menn, 1990). However, given that the proposed model involves preliminary cost estimates during the pre-design stages of a project, the current research focuses only on the seismic design parameters, the deck width and the length of the span supported by the piers. Since the majority of the construction projects (78% of the data sample) was designed with similar seismic parameters, the authors decided to exclude this parameter from the analysis and not to differentiate the proposed models based on the earthquake design parameters. Thus, the length and width of deck were the two independent variables included in the analysis. The volume of concrete (V_c), the weight of reinforcing steel (B_s), and the weight of prestressing steel (B_p) represent the three dependent variables.

Bridges with a superstructure consisting of precast prestressed simply supported concrete beams and composite reinforced concrete slab are typically designed to include several spans of equal length in order to use a large amount of standard precast elements, achieve standardization of the construction process, and reduce construction time, thereby achieving economy. The initial data sample considered all superstructure spans included in the 31 bridges constructed using this method. After excluding duplicate information, the sample includes complete data for 47 superstructure spans. The material quantities include the precast concrete beams, the diaphragms, the precast planks, and the composite slab.

In regard to motorway bridges with cast-in-situ decks, after considering all superstructure spans and excluding duplicate information, the final sample includes complete data from 47 superstructure spans consisting of cast-in-situ box girders. The material quantities do not include the sidewalks as they are constructed with concrete of a lower strength compared to the remaining deck and depend on the specifications of the highway.

The cantilever construction method is widely used for medium and long span concrete bridges when the ground morphology and local conditions render the use of traditional scaffolding difficult, impossible, or extremely expensive. This method consists of building a bridge deck through a succession of segments, usually starting from one or more piers, where each segment placed balances the weight of the next segment on the opposite side of the pier and occasionally the weight of the formwork (Mathivat, 1983). The stability of the resulting cantilever is secured at each step of construction by prestressed cables arranged according to the moment diagram of the cantilever; as a result, the material quantities of the superstructure depend on the length of the cantilever. The bridge database contains 15 structures constructed with the balanced cantilever method. After excluding the duplicate information, these bridges include 33 cantilevers that constitute the data sample. The material quantities do not include the sidewalks. The Pearson product-moment correlation coefficients for the dependent and independent variables were calculated for all cases and indicated that the length of the span or the cantilever presents the major impact on the material quantities; moreover, no evident problem due to multicollinearity exists. As a result, in order to reduce the number of variables and simplify the regression analysis, the adjusted length of span was defined as follows:

$$l_{sadj}=l_s \times \left(\frac{b}{b_{med}}\right) \qquad (1)$$

where l_{sadj} is the adjusted length of span, l_s is the length of span, b is the deck width, and b_{med} is the median value of the deck width. The adjusted length of the cantilever (l_{cadj}), similar to the adjusted length of span, was used for the cantilever-constructed bridges. The examined regression model included one independent variable in the following form:

$$Y=a+\beta_o \times X \qquad (2)$$

where Y represents the dependent variable (V_c, B_s, and B_p) and X represents the independent variable (l_{sadj} or l_{cadj}). Regression statistics for all cases, including the R^2, the significance of the F-test, and the p-value, are presented in Table 1 and highlight the goodness of fit and the statistical significance of both the regression model and the independent variable at a 1% significance level. Table 2 presents the pre-design material estimates models as well as the range of values of the independent variable and the median value of the deck width. The Pearson product-moment correlation coefficients for bridges with deck type precast girders are provided in Table 3.

	Precast beams			Cast-in-situ			Balanced cantilever		
	V_c	B_s	B_p	V_c	B_s	B_p	V_c	B_s	B_p
P-value	6.5E-19	1.1E-15	1.7E-17	6.4E-16	8.8E-14	1.5E-16	2.4E-19	3.9E-17	3.7E-18
R^2	0.826	0.758	0.799	0.764	0.707	0.779	0.926	0.898	0.912
F-Value	219.261	145.403	183.660	149.912	111.838	163.009	404.284	282.911	334.195
F-significance	6.5E-19	1.1E-15	1.7E-17	6.4E-16	8.8E-14	1.5E-16	2.4E-19	3.9E-17	3.7E-18

Table 1. **Regression statistics.**

	Precast beams	Cast-in-situ	Balanced cantilever
V_c	V_c = -77.184 + 11.349 x l_{sadj}	V_c = 3.865 + 9.849 x l_{sadj}	V_c = -1705.124 + 28.807 x l_{cadj}
B_s	B_s = -6306.255 + 1336.155 x l_{sadj}	B_s = 8274.962 + 950.703 x l_{sadj}	B_s = -460706.124 + 6729.826 x l_{cadj}
B_p	B_p = -5035.551 + 432.707 x l_{sadj}	B_p = -7047.660 + 604.149 x l_{sadj}	B_p = -150397.754 + 2113.073 x l_{cadj}
Range	$20.53 < l_{sadj} < 46.34$	$17.88 < l_{sadj} < 67.17$	$91.29 < l_{cadj} < 204.66$
b_{med}	13.10	13.50	14.00

Table 2. **Material estimating models.**

	b	l_s	V_c	B_s	B_p	l_{sadj}
b	1.000					
l_s	-0.140	1.000				
V_c	0.334	0.787	1.000			
B_s	0.399	0.711	0.854	1.000		
B_p	0.290	0.797	0.757	0.851	1.000	
l_{sadj}	0.379	0.862	0.911	0.874	0.896	1.000

Table 3. **Pearson product-moment correlation coefficients for bridges with deck type precast girders.**

Validation of the models

The R^2 values range from 70% to 93%, indicating that the proposed models provide a satisfactory fit to the data. The estimated p- and F-values also verify that the independent variables and the selected regression models are statistically significant, while the regression coefficients present theoretical correctness.

However, a good fit for a regression model does not always guarantee its validity. Cross-validation techniques are widely used to estimate generalization error, choose among various models, and evaluate the prediction performance of a model. Thus, a 10-fold validation method was implemented in which the dataset was randomly divided into 10 subsets (the folds) of approximately equal size. The regression modeling was then performed, omitting one of the subsets from training; the computed model and omitted subset were then used for testing. This procedure was repeated for all 10 subsets, and the selected error criterion was averaged. The Mean Absolute Percent Error (MAPE) was selected as the error measure. MAPE represents the average of deviations between predicted and actual estimates in absolute values expressed as a percentage of the actual estimate. MAPE values for all material estimating models, presented in Table 4, reveal that the proposed models are able to predict the actual superstructure material quantities with an average error of less than 20%. This error is considered acceptable according to the U.S. Department of Energy's directives for construction projects (1997), which propose an accuracy range of ±40% for planning/feasibility estimates prepared prior to conceptual design. In addition, Ritz (2004) proposes an acceptable accuracy range of ±25-30% for construction cost estimates prepared prior to the project's conceptual design.

The derived MAPE values can be attributed to the lack of standardization in the selection of the bridge deck cross section. DIN standards do not dictate the use of specific shapes or cross sections, but propose several design conditions and criteria that must be fulfilled. As a result, the bridge designer is able to choose the allocation of material use and derive the exact dimensions of the beam shapes and the deck cross section as long as the criteria are fulfilled. For example, for a particular balanced cantilever construction, the consumption of materials is influenced by the aspect ratio of the box girder, the relationship between the overall width of the top slab and the cantilever flanges, and the prestressing layout on both top and bottom slabs. Meanwhile, for a particular precast prestressed beam deck, the consumption of materials is influenced by various design decisions related to the formation of the cross section of the deck, such as the number of beams used and their slenderness, the type of the beams' section (T-type beam with a wide upper flange or I-type beam with a narrow upper flange), and the type of precast planks. Furthermore, bridge construction usually constitutes part of a larger construction contract that involves several bridges with different parameters. The designer selects the deck shapes for each structure while considering the whole project in order to maximize the construction process's standardization and achieve economy.

In order to assess the accuracy of the proposed cost method, the actual and predicted superstructure costs were calculated for each bridge from the data sample using current material unit prices. The developed estimating models were applied to derive estimates of the material quantities, which subsequently led to estimates of the total superstructure cost. The MAPE was calculated for each bridge deck; all values were averaged for each construction method (e.g., the average MAPE calculated for the cast-in-situ construction was 10.94%).

The correct application of the linear regression methodology with one independent variable requires three basic assumptions to be met—namely, the error term of the model should be normally distributed, have a mean value of zero, and have a constant variance (Gujarati, 1999). The residuals for the proposed regression models were calculated. The pattern of the residual plots was examined, indicating the sufficiency of the regression models. The assumption of normality was also tested with the use of the Shapiro-Wilks test (Shapiro and Wilk, 1965). This test examines the null hypothesis that the sample has a normal distribution and the calculated p-value denotes the probability of incorrectly rejecting the null hypothesis. A value greater than the level of significance leads to the conclusion that the sample is normally distributed. The p-values were calculated for each sample of residuals, verifying the normality assumption of the error terms at the 5% level of significance. Furthermore, the mean value of the residuals approached the value of zero.

White's (1980) general heteroscedasticity test was used to test the constant variance of the error term (i.e., the homoscedasticity of the regression models). This test, based on an auxiliary regression, does not assume a specific form of heteroscedasticity. The test statistic equals the product of the sample size with the R^2 of the auxiliary regression. The probability (p-value) of obtaining a chi-square value of the test statistic and the result of the test for a 5% level of significance are presented in Table 5, highlighting the presence of heteroscedasticity in the samples concerning the cantilever and the cast-in-situ deck construction.

Despite the presence of heteroscedas-

	V_c	B_s	B_p
Precast beams	11.66%	15.42%	16.14%
Cast-in-situ	14.48%	15.26%	19.30%
Balanced cantilever	14.76%	17.69%	16.03%

Table 4. **MAPE of prediction models.**

		Test statistic	P-value	Result
V_c	Precast	1.535	>0.25	Homoscedasticity
	Cast-in-situ	6.177	<0.05	Heteroscedasticity
	Cantilever	13.740	<0.005	Heteroscedasticity
B_s	Precast	1.851	>0.25	Homoscedasticity
	Cast-in-situ	7.604	<0.025	Heteroscedasticity
	Cantilever	9.167	<0.025	Heteroscedasticity
B_p	Precast	3.366	>0.10	Homoscedasticity
	Cast-in-situ	13.767	<0.005	Heteroscedasticity
	Cantilever	16.200	<0.005	Heteroscedasticity

Table 5. **Test statistic, p-value and result of White test.**

ticity, the ordinary least squares estimators remain unbiased, consistent, and linear (Gujarati, 1999), and the computed regression coefficients retain their validity. Meanwhile, the estimates of the variances are biased, thereby invalidating the tests of significance (Maddala, 1992). White's corrected standard errors were chosen to adjust for heteroscedasticity. MacKinnon and White (1985) raised concerns about the reliability of White's corrected standard errors for small samples and proposed three tests that should be used. Long and Ervin (2000) concluded that the HC3 test is the most reliable. The HC3's small samples corrected standard errors and the relevant p-values were calculated for all cases, verifying the statistical significance of the independent variables.

Bootstrap method for estimate ranges

The parametric cost estimate method, when used only with the proposed material estimating models, produces a single point estimate for the bridge superstructure cost. Probabilistic estimating techniques, such as bootstrap, attempt to provide additional information, assess the variability of the estimate, and ultimately quantify its level of uncertainty. Bootstrap belongs to a larger class of methods that resample from the original data set. Its most attractive feature includes its freedom from restrictive parametric assumptions and simplified models (Chernick, 1999). Bootstrap also benefits from its simplicity and alerts the practitioner to the data variability. It represents a computer-intensive method that is not only in general use by statisticians, but is also applied by quantitative researchers in various disciplines, such as engineering, life sciences, medical and social sciences, and business (Davison and Hinkley, 1997). The bootstrap method has been extensively used for the estimation of standard errors and empirical probability distribution functions of a population, regression and time series analysis, confidence intervals, and hypothesis testing. A recent application of the bootstrap approach can be found in Hughes and Paez (2006). A bootstrap resampling method, similar to the one applied by Sonmez (2008), was used in the current study to develop estimate ranges for bridge superstructure costs. The original data set for each model was resampled to form a new set of the same size as the original data sample. The elements of each sample were randomly chosen from the original data with replacements; as a result, the bootstrap data set consists of members of the original data set, some of which may have been chosen several times or not at all in any particular bootstrap sample.

The linear regression model presented in equation 2 was then applied to the bootstrap data set. The intercept and slope coefficients were chosen as the parameters of interest. The same process was repeated 1,000 times, and the numerous bootstrap iterations of the parameters were used to obtain bridge superstructure material estimates and predictions of superstructure cost. Finally, these estimates led to a probability distribution function for the predicted cost item as well as to the relevant range estimates.

Estimate ranges for case project

A combination of the proposed regression models and the bootstrap technique was used to develop superstructure material and cost estimates for a case project. The case example involved a single-span bridge deck consisting of precast prestressed simply supported beams with a composite slab. The values of the parameters are given in Table 6. One thousand bootstrap data sets, each containing 47 data points, were randomly drawn with replacement from the original data sample and used to develop 1,000 regression coefficients. These coefficients were utilized to make 1,000 estimates for the example superstructure material quantities, which subsequently led to predictions for the relevant superstructure costs by multiplying them with the unit prices. Table 7 provides estimate ranges for materials and superstructure cost at the 90% probability level as well as the relevant estimate figures derived by the proposed models, which approached the 50% prediction value. Figure 1 presents the empirical distribution function for the predicted total superstructure cost.

Parameter	Value	Unit
l	40.00	m
b	13.00	m
l_{sadj}	39.69	m
c_c	200.00	€ / m³
c_p	3.80	€ / kg
c_s	1.00	€ / kg

Table 6. **Parameter values for the case project.**

	Probability level			Model
	5%	50%	95%	estimate
V_c	361.9	373.2	383.4	373.3
B_s	45,253.8	46,686.7	48,078.7	46,725.7
B_p	11,741.2	12,137.8	12,632.0	12,138.6
C_c	72,383.9	74,646.9	76,684.5	74,651.6
C_s	45,253.8	46,686.7	48,078.7	46,725.7
C_p	44,616.6	46,123.5	48,001.5	46,126.6
TC	162,254.3	167,457.1	172,764.7	167,503.9

Table 7. **Estimate ranges for the case example.**

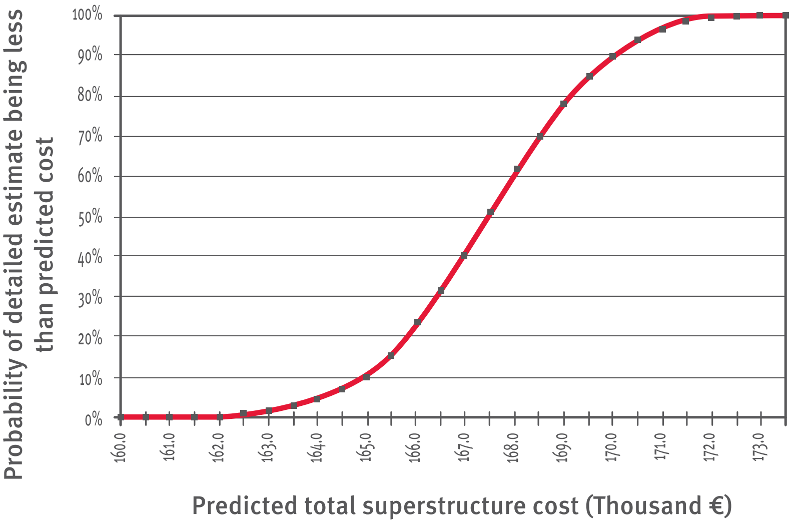

Figure 1. **Empirical probability distribution function for the predicted superstructure cost.**

CONCLUSIONS

The conceptual cost estimate method presented herein addresses the superstructure (i.e., the most costly component of the bridge) and applies to three widely used deck construction methods. The required input data consist of basic parameters identified during the preliminary study of a particular bridge. Linear regression was applied in order to derive the material estimating models necessary for the cost estimate. Not only was the fit of the models satisfactory, but also the basic assumptions of the linear regression methodology were tested and the necessary adjustments were made. The performance of the material estimating models was evaluated using the 10-fold validation method; the models' prediction error was considered acceptable for feasibility estimates.

A bootstrap method was also implemented in combination with the regression analysis in order to derive estimate ranges for the predicted superstructure costs. This probabilistic estimating

Name	Section	Seismic Zone	Width (m)	Length (m)	Deck Type	Construction Method
T6	11.3	II	12.70	210.00	Precast beams	Precast beams
Kompsatou	14.3.2	II	15.07	416.00	Precast beams	Precast beams
Erithropotamou	80.4	I	13.00	356.00	Precast beams	Precast beams
Kalogirou	4.2.2	II	12.10	280.00	Precast beams	Precast beams
Bridge 5 - L	13.5	II	13.10	270.00	Precast beams	Precast beams
Bridge 5 - R	13.5	II	13.10	345.00	Precast beams	Precast beams
Bridge 6	13.5	II	13.10	165.00	Precast beams	Precast beams
Votonosi - L	3.2	II	13.00	547.00	Box girder	Bal cantilever
Votonosi - R	3.2	II	13.00	536.50	Box girder	Bal cantilever
Bridge 2 – L	4.1.1	I	14.20	345.00	Box girder	Bal cantilever
Bridge 2 – R	4.1.1	I	14.20	349.00	Box girder	Bal cantilever
Bridge 12 – L	5.1	II	14.00	457.00	Box girder	Bal cantilever
Greveniotikou	4.1.5	II	12.78	920.00	Box girder	Bal cantilever
Mesovouniou	1.1.3	III	12.95	259.00	Box girder	Bal cantilever
Bridge 5 - L	2.4	II	13.50	240.00	Box girder	Cast-in-situ
Irinis	15.6	I	13.90	180.00	Box girder	Cast-in-situ
Bridge 12	14.3.1	II	13.95	145.00	Box girder	Cast-in-situ
Bridge 3	15.1.1	II	13.95	113.00	Box girder	Cast-in-situ
Bridge 4	6.0	II	13.50	135.80	Box girder	Cast-in-situ

Appendix A **Representative sample of the bridge database** technique was used in order to reduce the level of uncertainty inherent in the estimates.

References

Aparicio, A.C., Casas, J.R. and Ramos, G. (1996), "Computer aided design of prestressed concrete highway bridges", *Computers & Structures,* Vol. 60 No. 6, pp.957-969.

Belshey, D.A., Kuh, E. and Welsch, R. (1980), *Regression diagnostics: Identifying influential data and sources of collinearity*, Wiley, New York.

Brubaker, K.L. and McCuen, R.H. (1990), "Level of significance selection in engineering analysis", *Journal of Professional Issues in Engineering ASCE*, Vol. 116 No. 4, pp. 375-387.

Chernick, M.R. (1999), *Bootstrap methods. A practitioner's guide*, John Wiley & Sons Inc., USA.

Cohn, M.Z. and Lounis, Z. (1994), "Optimal design of structural concrete bridge systems", *Journal of Structural Engineering,* Vol. 120 No. 9, pp. 2653-2674.

Davison, A.C. and Hinkley, D.V. (1997), *Bootstrap methods and their application*, Cambridge University Press, USA.

Gujarati, D. (1999), *Essentials of Econometrics*, Irwin Mc Graw Hill, New York.

Hegazy, T. and Ayed, A. (1998), "Neural network model for parametric cost estimation of highway projects", *Journal of Construction Engineering and Management,* Vol. 124 No.3, pp. 210-218.

Hendrickson, C. (2008), "Project Management for Construction, Fundamental Concepts for Owners, Engineers, Architects and Builders, version 2.2", available at http://pmbook.ce.cmu.edu/05_Cost_Estimation.html (accessed 20 March 2008).

Hughes, W.O. and Paez, T.L. (2006), "Application of the bootstrap statistical method in deriving vibroacoustic specifications", paper presented at the 9th International conference on Recent advances in structural dynamics, July 17-19, Southampton, United Kingdom, available at http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20060056319_2006258493.pdf (accessed 14 March 2009).

Konstantinidis, D. and Maravas, A. (2003), "Egnatia Motorway concrete bridges statistics", in *31st ASECAP Study and Information Days proceedings of the international conference in Portoroz, Slovenia,2003*, pp. 92-109.

Long, J.S. and Ervin, L.H. (2000), "Using heteroscedasticity consistent standard errors in the linear regression model", *The American Statistician,* Vol. 54, pp. 217-224.

Lounis, Z. and Cohn, M.Z. (1993), "Optimization of precast prestressed concrete bridge girder systems", *PCI Journal*, Vol. 38 No. 4, pp. 60-78.

Lowe, D.J., Emsley, M.W. and Harding, A. (2006), "Predicting construction cost using multiple regression techniques", *Journal of Construction Engineering and Management*, Vol. 132 No.7, pp. 750-758.

MacKinnon, J.G. and White, H. (1985), "Some heteroskedasticity consistent covariance matrix estimators with improved finite sample properties", *Journal of Econometrics,* Vol. 29, pp. 53-57.

Maddala, G.S. (1992), *Introduction to Econometrics, 2nd edition*, Macmillan Publishing Company, New York.

Mathivat, J. (1983), *The cantilever construction of prestressed concrete bridges*, John Wiley & Sons Ltd., UK.

Menn, C. (1990), *Prestressed concrete bridges*, Birkhauser, Germany.

Miles, J.C. and Moore, C.J. (1991), "An expert system for the conceptual design of bridges", *Computers & Structures,* Vol. 40 No. 1, pp. 101-105.

Philbey, B.T., Miles, C. and Miles, J.C. (1993), "User-interface design for a conceptual bridge design expert system", *Computing Systems in Engineering,* Vol. 4 No. 2-3, pp. 235-241.

Ritz, G.J. (2004), *Total Construction Project Management*, Mc Graw Hill, New York.

Sarma, K.C. and Adeli, H. (1998), "Cost optimization of concrete structures", *Journal of Structural Engineering,* Vol. 124 No.5, pp.570-579.

Shapiro, S. S. and Wilk, M. B. (1965), "An analysis of variance test for normality (complete samples)", *Biometrika*, Vol. 52 No. 3-4, pp. 591–611.

Sirca, G.F. and Adeli, H. (2005), "Cost optimization of prestressed concrete bridges", *Journal of Structural Engineering,* Vol. 131 No. 3, pp. 380-388.

Skamris, M.K. and Flyvbjerg, B. (1997), "Inaccuracy of traffic forecasts and cost estimates on large transport projects", *Transport Policy,* Vol. 4 No. 3, pp. 141-146.

Sonmez, R. (2008), "Parametric range estimating of building costs using regression models and bootstrap", *Journal of Construction Engineering and Management,* Vol. 134 No. 12, pp. 1011-1016.

United States Department of Energy (1997), *Types of cost estimates - guide DOE G 430.1-1*, United States Department of Energy.

White, H. (1980), "A heteroskedasticity-consistent covariance matrix and a direct test for heteroskedasticity", *Econometrica,* Vol. 48, pp 817-838.