Spatiotemporal Visualization of Unit Price Data of Highway Projects

Deepanshi Jain[1], K. Joseph Shrestha[2], and H. David Jeong[3]

Abstract: The unit price contracting is the standard contracting method for highway projects in the U.S. As a result, state highway agencies have collected a large amount of historical bid data that they can use to determine engineer's estimates for future projects. The estimator must carefully consider various characteristics of a new project such as its location to determine an engineer's estimate as accurate as possible before bid letting. Higher cost estimates can result in the loss of the available budget and lower cost estimates may lead to deferral and delay of projects. The study uses the historical bid data obtained from Iowa Department of Transportation and develops a Geographic Information System (GIS) tool to visually show the variation of unit prices over the map using a spatial interpolation technique. The interpolation map can be used to estimate the unit price of the item at any location across Iowa. This noble method allows the estimator to effectively and fully utilize the historical bid data in a very time efficient manner and determine more accurate cost estimation.

Keywords: Unit-price-estimation, bid-data-analysis, GIS-visualization, spatial-interpolation

I. Introduction

The unit price contracting is the standard contracting method for highway projects in the U.S. In a typical highway project, the State Department of Transportation (DOTs) prepares a bid package including project plans and specifications, estimated quantity of each work item [1]. State DOT estimators also prepare Engineer's estimate, which is the final confidential document that is used to assess the bids that will be received and to select a winning bidder. Thus, it is important that unit prices are estimated accurately and effectively. Higher cost estimates can result in the loss of available budget and lower cost estimates may lead to delay of projects.

Typically, historical bid tabulation data available within sate DOTs is used to determine the unit prices of work items for a proposed project. Usually this bid data consists of various construction work items, which have been used for projects completed in the past along with the quantities associated with them. The estimator uses his or her experience and judgement gained over years to adjust the historical unit price according to upcoming project specifications. This adjustment depends on numerous factors like project size, location, availability of materials nearby project site, etc. [2]. Unit price estimation is a challenging task and heavy reliance on estimator's experience makes it more art than science.

Inaccurate cost estimation has been a source of error along with cost overrun of highway projects over time [3]. Costs are typically subject to fluctuations due to unit prices of work items varying according to market conditions, inflation, time and environmental factors [4]. According to reference [5], "the best that should reasonably be expected from such pre bid estimate is a reasonable approximation of costs that reflect many variables including the size, scope, complexity, and locality of a specific project."

Cost estimating guidelines of state DOTs do specify the need to consider factors of location, time, quantity of work, and others to adjust the unit price and estimate project specific unit prices but the establishment and use of any formal methodology to quantify the adjustment of unit prices is not common. In the study by reference [2], out of the 36 state agencies that replied to the survey, 82% reported that they did not have a formal process/ method to adjust the historical unit price for project location. It depends on estimator's judgment to quantify these factors and incorporate in the final unit prices.

In using the historical bid data to reasonably determine the unit prices of a new project, one of the main challenges is that the new project is likely to be at a different location. Thus, a proper interpolation is the most appropriate option to obtain unit prices for any location from the historical data. Interpolation results are based on Tobler's First Law of Geography, which basically means that points closer together in space are more likely to have similar values than points that are farther away [6].

This study aims to improve the cost estimation process for DOT estimators. The focus of this study is to analyze project locations and their effect on unit prices of major work

[1] Graduate Research Assistant, 394 Town Engineering, Department of Civil, Construction, and Environmental Engineering, Iowa State University, Ames, IA 50011, djain@iastate.edu

[2] Graduate Research Assistant, 394 Town Engineering, Department of Civil, Construction, and Environmental Engineering, Iowa State University, Ames, IA 50011, shrestha@iastate.edu

[3] Associate Professor, 404 Town Engineering, Department of Civil, Construction, and Environmental Engineering, Iowa State University, Ames, IA 50011, djeong@iastate.edu, 515-294-7271 (*Corresponding Author)

items. This requires a platform that can quantify unit prices while integrating the location of the project. Geographic information system (GIS) is used as a platform to map the location along with the data attributes associated with it. The study analyses the data and apply interpolation method(s) that are suitable for the data type. The study applies powerful interpolation tools available in GIS to integrate spatial information of projects with available bid data to obtain approximate values of unit prices for an unknown location. The validation is performed through the cross validation results obtained from the interpolation methods. The scope of this study is limited to the analysis of one major work item of Hot Mix Asphalt (HMA) Pavements and Portland Cement Concrete (PCC) Pavements across Iowa from 2011 to 2014.

II. Literature Review

Accurate estimation of future projects is vital for the optimum use of the available budget and to ensure that the funds are not allocated to the projects that cannot meet the current budget requirements [7]. State DOTs utilize Engineer's estimates for allocating funds for future projects [8]. According to the study conducted by reference [9], 20 state DOTs utilizes the lowest bids from historical projects to estimate the unit prices of work items for future projects. Such state-wide average values should then be adjusted for various other cost influencers. Project location is an important factor to be considered to improve estimation. Thirty-eight state DOTs reported that there is a wide variation in the unit prices across the state [10]. AASHTOWare Project Estimator® utilizes some form of regression for factors like work type, quantity, and project location for improved accuracy of the unit prices [11]. Yet, current practices of adjusting for the location are mostly based on the judgement of the estimators. However, with the development of GIS technology, there is a potential to apply such technology to generate more accurate cost estimates by taking the location or spatial factor into consideration.

GIS has been used in the past for various aspects of the construction industry to improve, digitize, visualize, track, and solve problems of spatial and descriptive data. One of the earliest uses of GIS in the construction industry was done by exploring potential construction sectors that can benefit by using the GIS technology [12]. GIS has been used widely in many aspects of construction. For example, it has been used for decision support system for selection of proper location for facilities [13] . It has also been used for processing, analysing, and modelling housing and mortgage data sets [14] and for estimating commercial property prices through spatial interpolation methods [15]. Similarly, the GIS technology has been used to adjust project cost estimates of building construction projects by location [16]. The overall tendency of the highway construction industry to rely on the estimator's ability and judgment is mainly attributed to the lack of validation of some of the most common methods and processes for performing estimates. Geo-statistical toolbar in ArcMap has various types of spatial interpolation methods that can be used for the unit price interpolation of bid items. References [15] and [16] identified that Inverse Distance Weighting (IDW) and Kriging are two advantageous interpolation methods for construction cost indexes and commercial property prices respectively. For this study, those two techniques are considered. These two interpolation methods are described in brief below:

1) Inverse Distance Weighted

This is one of the most frequently used deterministic techniques of spatial interpolation [17], which was originally called an approach using weighted averages [18]. As the name suggests, the attribute value of an un-sampled point is the weighted average of known values within the neighborhood, and the weights are inversely related to distance between the prediction location and the sampled locations [17]. The advantages of this method are it is relatively fast and easy to compute, and relatively straightforward to interpret [17].

2) Kriging

It is a geo-statistical technique i.e. it is based on statistics and are often used for more advanced prediction surface modeling that also includes some measure of certainty or accuracy of prediction [19]. This method is often used in fields related to construction. The theory behind this surface interpolation technique was developed by [20]. Kriging weights are generated from semi-variogram developed by viewing spatial structure of the data unlike a simple algorithm based on distance in IDW.

Each spatial interpolation method has its own advantages and disadvantages depending on the type of data they are used to interpolate [19]. Before applying the techniques, the dataset should be analysed for applicability of the methodologies.

III. Methodology

The study utilizes bid data of Hot Mix Asphalt (HMA) and Portland Cement Concrete (PCC) pavement projects of Iowa Department of Transportation from 2011 to 2014. Lump sum work items are removed from the dataset before selecting the top items in terms of frequency and total dollar amount of each work items in each year. The top three items for HMA pavement projects identified from the analysis are:

- Asphalt Binder, PG 64-22,
- Asphalt Binder, PG 58-28, and
- Hot Mix Asphalt Mixture (1,000,000 ESAL), surface course.

Similarly, top two items identified for PCC pavement projects are:

- Standard or slip form Portland cement concrete pavement, and
- Excavation class 10, roadway and borrow.

This paper presents the results for the analyses performed for Asphalt Binder, PG 64-22 using geo-statistical toolbar in Arc Map. The three data exploration tools used are histograms, normal quantile plots, and trend analysis. Histograms are used to assess the symmetrical distribution of data in terms using skewness and kurtosis value. Normal Quantile plots are used to determine if the data is normally distributed. Similarly, trend analysis is used to identify the anisotropic or directional trend of the bid data, if any. Those analyses are performed to determine the suitability of dataset for application of Kriging and IDW interpolation methods.

Bid data from 2011 to 2014 are analysed year-wise as well as after being combined together. To take care of the temporal variation of the unit prices over years, approximate inflation rate for the item is calculated based on the average unit price of the item for each year. All the unit prices are converted to the base year 2014 using the inflation rate calculated. The spatial interpolation map developed with the base year 2014 (compared to 2011) is more relevant to calculate the unit prices for future projects. A cross validation analysis is performed afterwards to evaluate the accuracy of the interpolation map developed and validate the analyses.

IV. Results And Analysis

This section presents the results of the data exploration analysis to understand the distributions of the data using various geo-statistical tools followed by the results of the application of various interpolations techniques.

The results of the histogram, normal quantile plot, and trend analysis of Asphalt Binder 64-22 showed that the bid data is not symmetrical, nor normally distributed. Analysis of the data for each year showed that there is a directional trend in one direction or others for dataset of each year. Because of the non-symmetric and non-normal dataset, Kriging is not the preferred interpolation method for the dataset. To apply Kriging, such data needs to be transferred to remove the directional trend. This adds complexity for utilizing the methodology by state DOTs that have limited resources for generating estimates. Thus, IDW is selected as a sole method for generation the interpolation results. IDW does not require such data transformation or trend fitting, and can be applied directly to the dataset for obtaining a smooth interpolation easily.

The results of the IDW for Asphalt Binder, PG 64-22 is presented in Figure I. The four bid price maps show the results for each year from 2011 – 2014 with 2011 results at the top and 2014 at the bottom in a chronological order. Each map in the figure is color-coded with red color representing higher unit prices and blue color representing the lower unit prices. It is evident from the figure that for year 2012, the unit prices of the Asphalt Binder, PG 64-22 is higher in all regions compared to other years. While the locational variation in the unit prices is very high, it also shows some areas where the unit prices are consistently lower or higher or in-between.

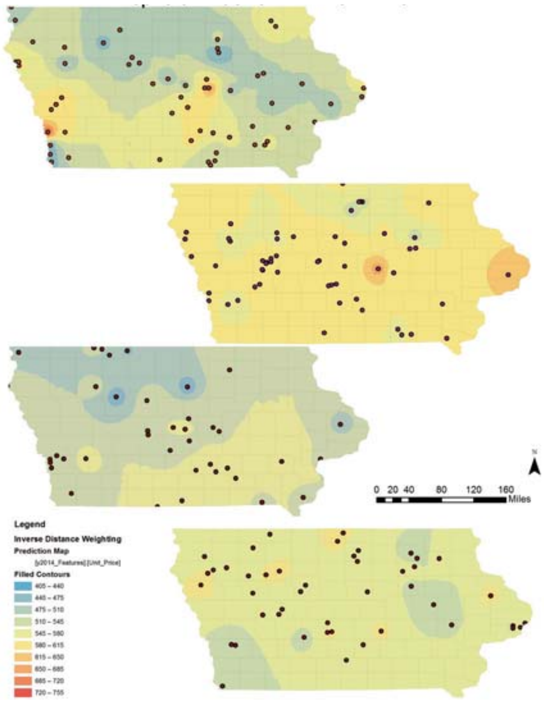

FIGURE I

IDW FOR ASPHALT BINDER, PG 64-22 (YEAR 2011 - 2014)

For example, the south-west region of the state has usually lower unit prices. The exception is the year 2012. But, it may be noted that there was no actual data point in the south-west side for that year. Thus, while the region has been consistently lower than the other areas, the map showed different result for year 2012. Such limitations can be taken care – in part – by obtaining more data that have more locational coverage. Thus, another bid price interpolation map for Iowa is also prepared by combining the dataset from all the years (2011 – 2014). Converting the unit prices for the bid item from year 2011 – 2014 to a common base year of 2014 combines the dataset. The average unit prices of the item and the item-specific approximate inflation index used to convert the unit prices from all years to 2014 are presented in Table I.

TABLE I

ANNUAL AVERAGE UNIT PRICE DATA AND INDEX (BASE YEAR 2014)

Year	Average Unit price	Index with base year 2014
2011	540.37	1.04
2012	586.08	0.95
2013	527.85	1.06
2014	561.90	1.00

The interpolation map obtained from the combined dataset is presented in Figure II. The map has more granularity because of the use of more data points.

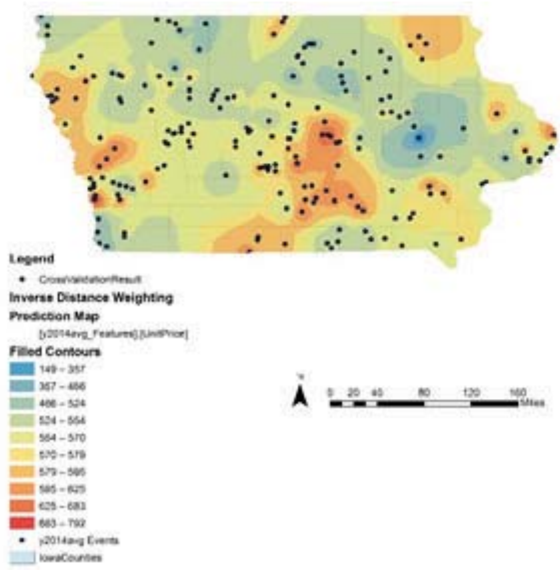

FIGURE II

IDW RESULTS FOR UNIT PRICE DATASET CONVERTED TO YEAR 2014

The cross validation results of the interpolation maps developed are summarized in Table II. The results show that the interpolation map is most accurate when the data from all four years are combined. This is possibly because of the availability of more data for generating more granular interpolation map.

TABLE II

CROSS VALIDATION RESULTS

Year	Absolute average error	Average unit price	Percentage error (%)
2011	37.06	540.37	6.86
2012	18.46	586.08	3.15
2013	29.42	527.85	5.57
2014	18.04	561.90	3.21
Combined (base year 2014)	20.96	559.51	3.75

The errors obtained from the cross validation results is very low and hence the interpolation maps can be used by state DOT personnel to estimate unit prices of the Asphalt Binder, PG 64-22 for future projects. Approximate estimates can be obtained by visually inspecting the map.

V. Discussions, Conclusions, And Recommendations

This study presents the application of powerful spatial interpolation tools for spatial interpolation of the unit price bid data using the Asphalt Binder, PG 64-22 as an example. The maps developed in the study are visual and can be used to quickly determine a reasonable unit price of a work item and it could be used to defend the estimate results. It is also effectively used to communicate with the upper management in project budget allocation process. The bid data is also used for the temporal analysis of the unit prices to see the temporal trend. Once the location of a new project is known, the estimated unit price of a work item can be obtained by just clicking on the new project location in the interpolation map on GIS.

This study presents the methodologies to consider both spatial and temporal unit price fluctuations and hence the use of the methodologies presented is expected to improve the certainty of future project costs. Future studies should consider the use of additional spatial cost influencers such as location of asphalt plants, number of bidders likely to bid in a project in a given location, etc. and other cost influencers like item quantity in addition to the location of the projects to improve the cost certainty.

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