Analysing Construction Cost Estimation Factors as a Map

Kambiz Borna, Duaa Alshadli, Antoni Moore

***Abstract*—** For construction projects, different factors such as the type the of project, material costs, project conditions and duration are combined to estimate the total project cost. Hence it is essential for the relationships between these factors to be well-defined in order to produce an accurate cost estimate of each stage of the project. The aim of this paper is to formulate and implement a Geographic Information System (GIS)-based approach that allows the user to properly quantify and visualize the relationship between these (non-spatial) factors in a virtual geospatial space, providing accurate cost estimates. To achieve this, Voronoi polygons are used in the developed method to transfer duration and completion time of each project stage from one-dimensional data into a two-dimensional space (spatialisation). A sigmoidal shape is then utilised as a profile and scaled to convert the two-dimensional map into a three-dimensional map based on the material costs and difficulty of each activity. This provides a visualization tool that is similar to a topographic map. The generated maps are then compared to quantify and identify inconsistencies between duration, difficulty and cost of each activity for a house-construction project. The results demonstrate the effectiveness of this method in identifying the best cost estimation scheme.

***Keywords*—** Construction project, Cost estimation process, GIS, Spatialisation.

I. Introduction

In a construction project, the cost estimation process is usually performed based on parameters such as project size, type of project, material costs, duration, and ground conditions [1]. The relationship between these parameters is mostly defined and modelled by a human expert such as a project manager or builder and this can create inconsistencies in estimation [2]. Hence, it is important that these factors and the relationships between them are properly addressed in an applied model to create an accurate cost estimation proposal [3]. To achieve this, different intelligent construction cost estimation techniques can be applied. For example, [4] used Support Vector Machines (SVMs) to assess the quality of conceptual cost estimates. They examined different factors such as availability of data, quality of drawings and the estimator's experience to evaluate the quality of the cost model. A genetic algorithm was utilised by [5] for project scheduling. The model used time, cost and allocated resource to identify the starting point of each project activity. Reference [6] employed Artificial Neural Networks (ANNs) to analyse the cost and duration for the road construction project.

These methods have two main common characteristics. First, they usually employ attribute data in a non-geographic space to define the relationship between the parameters. Second, the use of the methods requires the expertise of the human professional [3], [6].

This paper presents a new method that uses Geographic Information System (GIS)-based spatialisation [7] that allows us to integrate, visualize and evaluate the relationship between the parameters, e.g. time, cost and physical conditions in a three-dimensional map-like space. Applications of GIS for project management have already been addressed in several studies. For example, [8] used GIS tools to monitor the progress of a construction project in a four-dimensional space by implementing a 4D view to identify the logical errors that occur in project schedules. [9] used GIS to simultaneously assess the effect of spatial and non-spatial parameters on the construction site. A GIS-based tool was developed by [10] to integrate data from different sources to identify inconsistencies in geometric visualization and coordinate transformation in hydraulic engineering projects. These methods typically rely on spatial data to create 3D views or to integrate data from different sources, but are not used for applications involving non-spatial data. As a precedent for the current approach, [11] presented a GIS-based spatialisation method for time and project management that can accommodate non-spatial data. They used GIS tools and concepts such as segmentation and interpolation to visualize and monitor different projects based on two non-spatial factors, namely difficulty and duration and converted them to a three dimensional map.

To address the relationship between construction factors in the cost estimation model, this paper presents an approach formulated on the notion of forming a spatial representation of non-spatial phenomena, i.e. spatialization. To perform this process, each stage of the construction project is initially considered as a point feature distribution in an abstract 2D space. The proposed method extracts Gantt chart attributes to locate each point in the space. The coordinate of each point is determined in terms of the duration and completion time factors of each stage. In this way, the map represents the project stages as spatially ordered into order to depict an abstract view of the cost estimation proposal schedule. The points are processed to generate their own areal zones through the construction of a duration-weighted Voronoi diagram.

The generated two dimensional representation provides the necessary framework to construct a three dimensional

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topographic map based on the remaining non-spatial factors such as difficulty and cost. This approach enables us to analyse the cost of a project within a unified data structure, namely a map; based on different construction factors. This allows the relevant stakeholders, e.g. property owners, lenders, or builders, to readily, consistently, and accurately share the construction project information.

II. Method

A. Project Factors

In a construction project, cost estimators apply different factors such as duration, cost and completion week to itemize each stage of construction. The values of these items are usually determined based on the estimator's experience in terms of a percentage of total costs of the completion and the project conditions of each stage. Table I shows an example of a house construction project that is itemized based on the different stages of the project, their completion week, duration, difficulty and cost allocation. Difficulty is the factor determined based on the physical conditions of each stage.

There are two cost lists, Cost A and Cost B, which are proposed by two different estimators based on a percentage of the total allocated cost. The aim of the proposed model is to compare these two lists in terms of the construction factors and identify the best cost estimation plan.

TABLE I
SIX DIFFERENT STAGES FOR A HOUSE-CONSTRUCTION PROJECT

Project stage	Completion week	Duration	Difficulty	Cost A	Cost B	Predecessor
Clearing of the site	Week 2	2 weeks	2	5%	6%	……..
Base stage	Week 8	6 weeks	3	15%	13%	Activity 1
Frame stage	Week 15	7 weeks	4	20%	23%	Activity 2
Lockup stage	Week 18	4 weeks	4	20%	22%	Activity 3
Fixing stage	Week 22	6 weeks	5	30%	27%	Activity 4
Practical completion stage	Week 24	2 weeks	3	10%	9%	Activity 5

The method is implemented in three main steps: creation of the 2D spatialized map, construction of the 3D topographic map and production of the consistency map in terms of a percentage of total costs of the completion and the project conditions of each stage. The algorithm is implemented using Repast, a Java-based Toolkit on an Intel CPU at 1.70 GHz and 4 GB of memory. ArcGIS 10.5 is also used to represent the 2D and 3D views of the generated maps.

B. Creation of the 2D spatialized map

In the proposed method, the task duration and due date values from Table I were used as coordinates to convert and transfer them into a two-dimensional space as a point. As the number of stages are limited and the relationship between them is sequential, the model of Gantt chart was applied for time mapping. In this case, the x-axis and y-axis are the corresponding duration and completion week of each stage, respectively. Thus, each stage is represented by a point specified by $S_n(x_n,y_n)$ in which x_n and y_n are a function of the duration and completion week of each stage, respectively. In the next step, the method employs a Voronoi diagram to divide the 2D space (that is represented as a grid of regularly-sized cells, the points of which are specified by $P(x_p,y_p)$) into a set of regions. The method employs the metric below to create Voronoi polygons.

$$d_{Sp} = {}^{1}/_{TD} \sqrt{(x_n - x_p)^2 + (y_n - y_p)^2}, \quad (1)$$

Where TD is the duration, x_n and y_n are the coordinates of each stage in the 2D space and x_p and y_p represent the coordinate of each point P in the 2D space. $S_n(x_n,y_n)$ at each stage are denoted with single points in Fig. 1. $P(x_p,y_p)$ are the points determined by cells in Fig. 1, and d_{Sp} is the weighted distance.

The algorithm uses the minimum weighted distance for each point P to allocate that point to one of the stage points S_n, thus segmenting the 2D map. In Fig. 1, each region corresponds to one stage of the project, the area of each polygon in proportion to the stage duration.

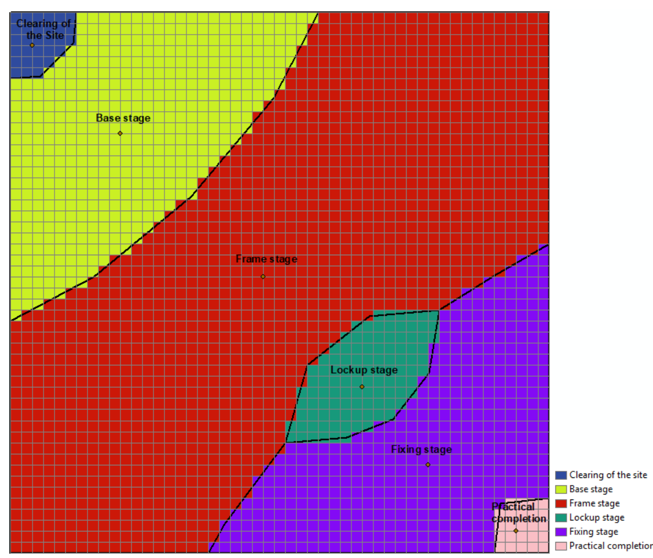


Fig. 1 The weighted Voronoi polygons in the 2D space.

C. Construction of the Topographic Map

There is a strong relationship between cost, duration and project conditions such as difficulty [12]. This relationship is typically defined based on an exponential function [13]. The model used in this study employs a sigmoidal shape [14], to transfer the cost and difficulty factors from Table I to add a "height" dimension to the 2D space. Equation (2) was used to perform this transformation [11] and is used to calculate the height for every P within a stage region, based on its distance from stage point S_n.

$$Sigmoid\ (d_{Sp}) = \left({}^{1}/_{1 + e^{-norm\,(d_{Sp})}}\right) \times C_n \quad (2)$$

Where C is the condition project of each stage, and in this case, it represents the difficulty at each stage number (n). The normalized distance is depicted as $norm(d_{Sp})$ and ranges between -5 and 5 within each stage region.

The output of the model is a topographic map where each hill represents the difficulty of each construction stage (Fig. 2).

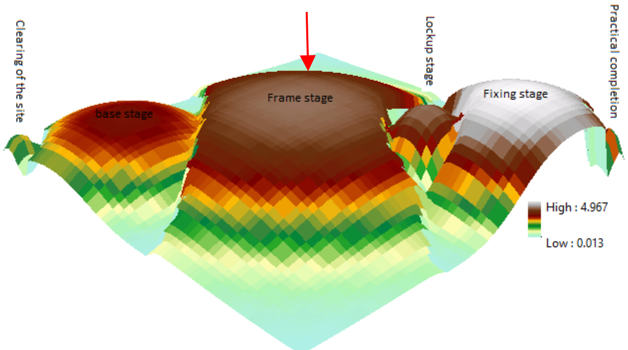
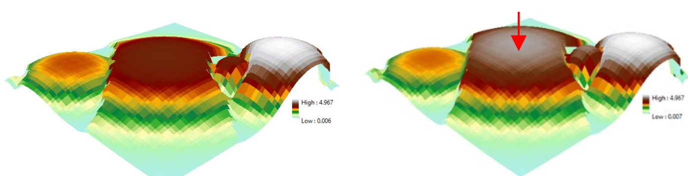


Fig. 2 The difficulty map for each stage.

Equation (2) is then applied to create two 3D maps based on Cost A and Cost B. In this event, C values are specified based on the Cost A and B lists. Fig. 3 displays these two maps in a 3D topographic spatialisation.



(a) (b)

Fig. 3 (a) and (b) are the 3D views of the Cost A map and Cost B map, respectively,

A visual assessment of the 3D maps based on elevation values shows that the elevations of the 3D Cost B map are similar to the corresponding points in the difficulty map (red arrows on Fig. 2 and Fig. 3(b) for the Frame stage). In contrast, this elevation difference is evidently different for the 3D Cost A map. This means that there is no balance between the difficulty and the allocated cost for the Frame stage in Cost A, whereas there is a balance in Cost B.

D. Production of the Consistency Map

In this step, the difference between the Cost A map and the difficulty map was used to generate a consistency map A (Fig. 4). The created map is divided into three categories:

- Inconsistent group - includes the points where the elevation difference between the corresponding points on the difficulty map and the Cost A map is greater than 0.25.
- Partially consistent - displays the locations where the elevation difference between the difficulty map and Cost A map is in the range of 0.1 to 0.25.
- Consistent group - displays where the elevation difference between the difficulty map and Cost A map is less than 0.1.

According to Fig. 4, the cost distribution is unbalanced for the frame, base and lockup stages. Because the elevation difference values are positive, the red area on the consistency map can be decreased by increasing the allocated budget for these three categories.

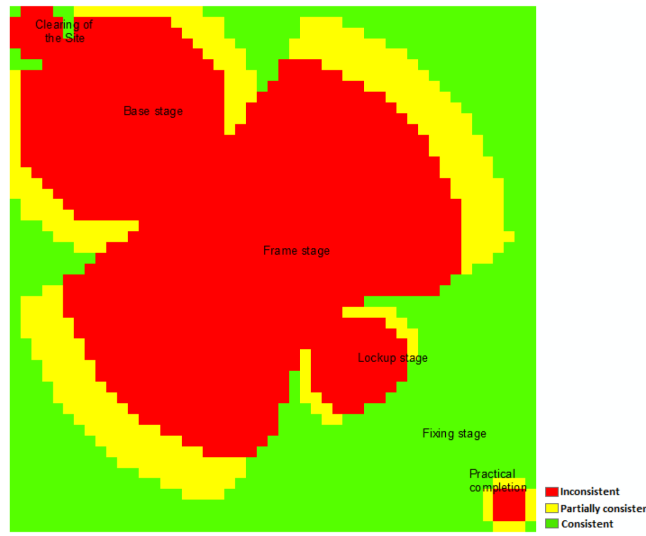


Fig. 4 The consistency maps for Cost A in the 3D abstract space.

In the same way, the Cost B map and the difficulty map are applied to create the consistency map B shown in Fig.5. This map shows that there is an inconsistency for the base stage in cost B. To overcome this problem, we can increase the allocated cost of the base stage in cost B (Table I).

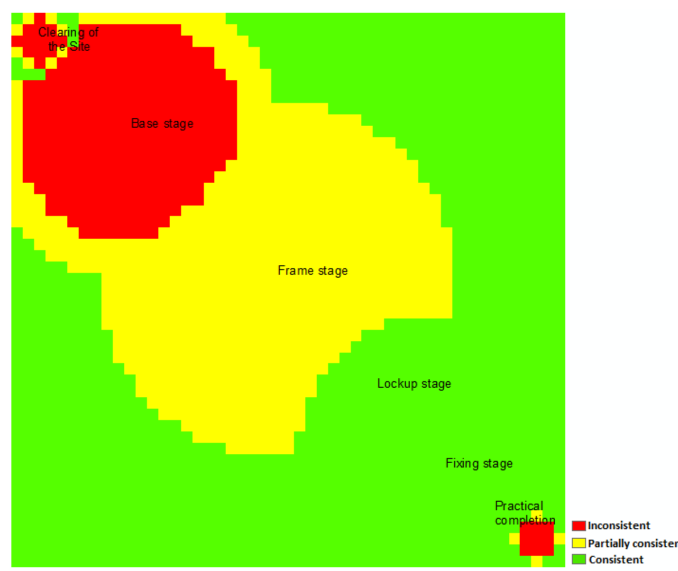


Fig. 5 The consistency maps for Cost B in the 3D abstract space.

A visual assessment of these two maps demonstrates that the Cost B scheme is more accurate than the Cost A scheme in terms of the allocated time and difficulty of each stage. Table II lists the area of each cost group from Figs. 4 and 5. As shown, there is a sharp difference between the inconsistent areas on the two maps.

TABLE II
THE AREA OF EACH COST CATEGORY

Proposal	Consistent	Partially consistent	Inconsistent
Cost A	866	390	1145
Cost B	1202	858	341

III. Conclusion

The Cost estimation process is an important stage in a construction project and it involves different parameters that need to be simultaneously analysed to provide an accurate cost estimate. This paper highlights a new method that allows us to map the relationship between different non-spatial factors in the cost estimation model and to spatially display this information as maps in 2D and 3D map-like spatialisations. The generated maps are then used to quantify the relationship between parameters and further create inconsistency maps, which can then be used to better estimate the project cost for each stage, and to provide a more consistent and reliable method of cost estimation for relevant stakeholders. Moreover, the use of the applied method allows us to identify unbalanced project stages in terms of the project factors and to update any initial balanced cost lists. The results demonstrate the high potential of the proposed method to estimate the cost for a house-construction project and can be scaled up for use on more complex construction projects. The implementation of a more complex scenario and the integration of other factors would be interesting for further research.

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