An Innovative Approach for Generation of Virtual Construction Model and a Time Location Plan for Road Construction Projects

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ABSTRACT: Construction managers require innovative techniques to assist them in producing accurate planning tasks such as resource allocation and costing of activities, because of unique characteristics of the road construction industries. The research study introduced a framework for Virtual Construction Model (VCM) that includes 4D modeling and automatic generated time location plan for earthwork activities in a road project. The framework is designed by integrating road design data, quantities of cutting and filling sections, variable productivity data, algorithms for 4D terrain modelling, and a progress profiles visualiser. The model is validated with a real life case study of a road project and it was found to be beneficial in generating the 4D terrain surfaces of progress, cost histogram and a time location plan with more accurate information of location and time in the earthwork operations. The VCM has potential to assist project planners and construction managers in producing efficient construction scheduling and resource planning.

1. INTRODUCTION

The planning, scheduling, and controlling system adopted by planners/ construction managers determines the success of any construction projects. Construction managers and project planners of linear construction projects such as roads, railways, and pipelines require advanced project planning and scheduling tools to control budget, schedule and resource allocation so that project goals could be achieved on time and on budget. The effective application of planning and scheduling techniques such as CPM and PERT is limited because road construction activities are fundamentally different to building construction projects (Hamerlink and Yamin, 2000).

In a large-scale project, a visual representation of the construction schedule can be extended to monitoring not only the construction progress, but also all the auxiliary activities, including onsite plant and equipment (Adjei-Kumi et al, 1996). McKinney et al (1998) demonstrated the capability of 4D-CAD models to identify the construction problems prior to their actual occurrence. The failure to provide the information of spatial aspects of a construction project by traditional techniques such as Bar Charts and the Critical Path Method (CPM) have motivated the research effort to incorporate visualisation techniques into project scheduling and progress control (Koo and Fischer, 2000). Zhang et al (2000) further developed a 3D visualization model with schedule data at the level of construction components. Kamat and Martinez (2001) presented a 3D visualization model depicting the entire process of a typical construction activity. Dawood et al (2002) developed an integrated database to act as an information resource base for 4D/VR construction process simulation and it was applied to a building project.

Furthermore, several research efforts carried out in the visualisation of the construction process applied to building construction projects, but there have been limited research studies in the area of infrastructure construction projects. For example, Liapi (2003) focused on the use of visualisation during construction of highway projects to facilitate collaborative decision making on construction scheduling and traffic planning, however, the visualisation of the construction schedule for the intermediate stages of the construction process was neglected.

Castro and Dawood (2005) developed the "RoadSim" simulator based on the site knowledge-based simulation system. It is applicable to develop a master construction schedule in a road project based on simulated productivity of road building activities and available resources with different sets of equipment and site working conditions. Kang et al (2008) suggested an approach to simulate 4D models for the movement of earthwork activity for the intermediate stage of the construction process in civil engineering projects using morphing techniques and realisation of construction progress in graphical images. The 4D models of earthwork operation have been produced in 3D CAD model at equal volume and at a fixed production rate of the earthwork activities at different stages during construction operation and linked with time but the variable productivity data of equipment and soil characteristics was not considered in the 3D CAD models.

The above research efforts did not address the interface of variable production rate, which depends on available resources and site conditions for the development of the VCM. The key issue faced in road construction sites is the variable productivity from one day to another due to the special characteristics of the road construction industry; such as fluctuation in daily weather conditions, working conditions in open sky, resource unavailability on time and other unpredictable factors.

The study focuses on addressing the above issues by the development of the VCM. The model will be integrated with the "variable production rate" of earthwork activity throughout road construction operations. Currently accepted scheduling techniques including CPM, PERT and Bar Charts are unable to model linear activity more accurately in terms of locations. A linear scheduling method developed earlier than CPM has the potential to provide significant enhancement, because it provides location of working activities coupled with the advancement of computer technology. This allows the project schedulers and construction managers to plan road construction project visually to determine the controlling activity path (Hamerlink and Yamin, 2000).

Previously research efforts by Johnston (1981 and Garold et al (2005) in the area of linear scheduling concluded that the techniques are a useful schedule ing tool for progress monitoring in road construction projects during the planning and execution phases. Previous research studies have considered earthwork activities as a linear activity (Hamerlink and Yamin, 2000). However, earthwork activities are nonlinear in real practice since the earthwork quantities vary along a road project from station to station (chainage to chainage) according to topography of terrain surfaces.

To overcome this issue of the earthwork activity, this study presents an innovative methodology for the development of VCM and a time location plan of the earthwork construction processes in road construction projects. The VCM generates 2.5D terrain surfaces of road profiles automatically at the intermediate stages during the earthwork operations. The model intends to assist in improving the site communications of road construction planning and scheduling information, and to produce efficient construction scheduling and resource planning. The remainder of this paper outlines a conceptual framework and details of the prototype for VCM and generation of a time location plan of the earthwork operations in a road project.

2. FRAMEWORK OF A VIRTUAL CONSTRUCTION MODEL (VCM)

The general specification of framework of a prototype of virtual construction model is outlined in figure 1. The framework integrates the road design data, sectional quantities of cut and fill, productivity models, algorithms for terrain modelling and a progress profile visualiser. The model assists in generating visual terrain surfaces of road progress automatically throughout the earthwork operations. The next section describes in detail the input, process and output of the VCM.

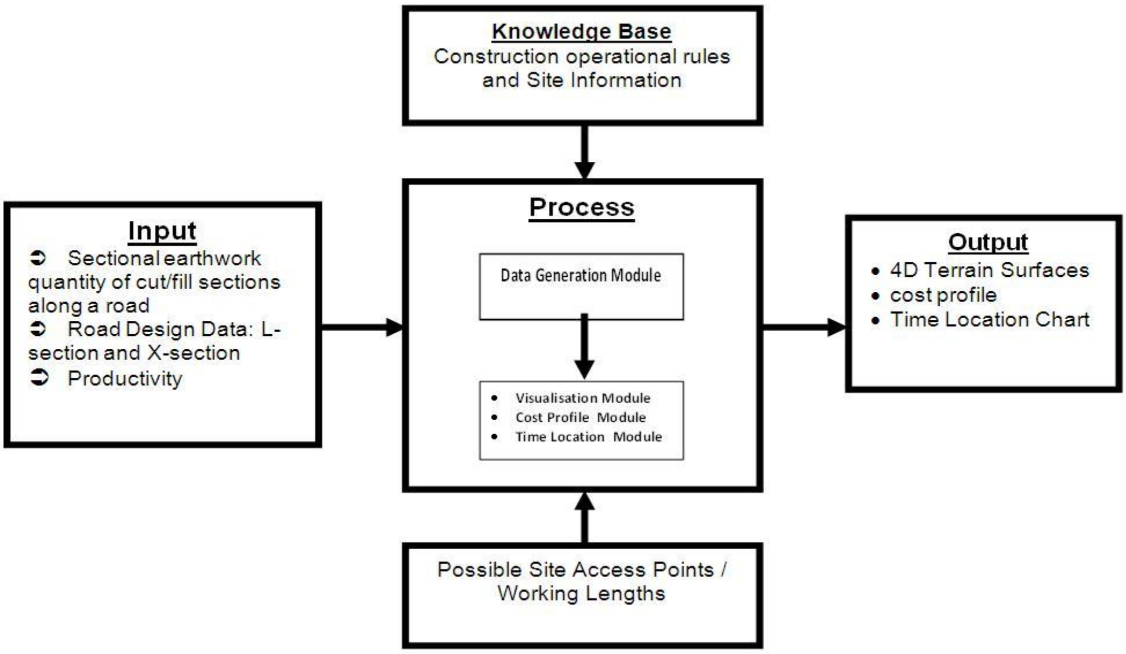


Figure 1: Framework specification of a virtual construction model

2.1 Input

The sectional quantities of cut/fill of earthwork activity along a road section, productivity of the activities and construction site knowledge base are key components of the framework. The sectional cut/fill quantities are calculated using road design data including L-sections and X-sections at required intervals of chainage. The productivity data, which is produced by the "RoadSim" simulator, is used as a key input in the model. The productivity is calculated using the available resources, equipment sets and site working conditions. This is incorporated with the model to determine the total duration of the earthwork operations. The soil characteristics along the working road section, types of available equipment set for a selected activity, haulage distance of soil, working conditions and all other factors including weather conditions that control productivity has already been incorporated within the "RoadSim" simulator. Additionally, the model will assist in identifying the possible location and numbers of site access points. The construction knowledge will assist to select the methods of construction process for different types of soils, equipment sets for a particular activity and soil characteristics. The site operational rules allow in establishing the sequential relationships amongst listed activities during the construction operations. The following section describes and demonstrates the process of the VCM.

2.2 Process

The process of the framework includes four modules: data generation module, visualisation module, cost profile module and a time location module. Data generation module processes the input data to produce a detailed schedule and to generate the coordinate data of terrain surfaces based on the production rate i.e. on the weekly basis in this study. The visualisation module processes the coordinate data produced by the data generation module, and converts it into terrain surfaces of the road progress profile in a regular triangular grid. The cost profile module generates weekly cost profiles/histograms and the time location module generates a time location chart of the earthwork operations in road projects. Details of time location module and conflict identification system are presented in the following sections.

2.2.1 Generation of Time Location Chart

In this section, a set of algorithms is developed to automate the generation of terrains of earthwork activities at different stages of the construction process. This is considered the quadratic equations, which determines the progress height for earthwork activities. A detailed development for the generation of weekly coordinate data presented by Shah et al (2008) is used for the generation of a time location chart in this research study.

The time location chart is also known as time-distance planning, time-chainage planning and linear scheduling method (LSM). It enables the creation and display of planning and scheduling information of earthwork activities in two dimensions: Location in X-axis and Time in Y-axis or vice versa together with the topographical information of a road project. The slope of activities displayed in time location chart represents the rate of productivity. The slope of activity provides the early indication of conflicting or overlapping activities that may occur during the course of activity progress.

An algorithm was designed to identify the start and end location as well as start and end time of earthwork activities. The developed algorithm determines the location (chainage) along a road section and are broken down into weekly schedules satisfying the linearity characteristics (start and end locations having equal production rate) of the earthwork activities. The identified locations and time are summarised and presented in a table. A linear schedule of the earthwork activities is generated from the tabulated locations and time as (coordinates of the starting and ending points of weekly earthwork activities) developing a module (macro) based on using VBA language.

The generated time location chart provides clearer representation of a construction schedule and enables the visualisation and analysis of the status of construction activities on a particular location along the road sections. It also supports in identifying the possible conflicting/overlapping locations along the road section. The detail of the development of conflict identification system is described in the following sections.

2.2.2 Development Conflict Identification System (CIS):

This section focuses on exploring and developing a new methodology in which the VCM can be enhanced to represent earthwork scheduling and planning information in a time location chart (TLC) and to identify the possible conflicting points. It is envisaged that TLC will provide more accurate information in terms of location through integrating with a real site operations and incorporating actual earthwork progress data with the VCM. In this way, the model enables the integration of real site data of soil profiles and assists to update site productivity in earthwork operations according to soil characteristics along a road project and scheduling information is represented in a time location chart. The flow diagram of the conflict identification system (CIS) is presented in figure 2 and the details of the flow diagram are described below.

The conflict identification system is important to construction managers and project planners in order to identify the possible overlapping activities in advance so that space conflicts, wastage of resources, idle equipment and reduction in site productivity can be resolved at planning stage. It is anticipated that conflict identification system can assist to reduce the remaining difficulties encountered by construction managers when allocating resources and monitoring the site progress.

To resolve the above issue, this research study focuses on a conflict identification system in a road project including earthwork operations.The functionality of VCM has been improved by incorporating a new approach, which is useful to identify and determine the overlapping or conflicting points in terms of location and time along a road section between two activities in earthwork operations.

The conflicting identification system (CIS) is expected to assist project planners and construction managers in identifing and determining the coordinates (location and time) of the conflicting/overlapping points having different productivity value and passing through different site access points. The location and time of conflicting/overlapping activities during earthwork operations can also be analysed considering the soil characteristics along a road section.

The system enables project planners and construction managers to take preventive measures by forecasting the possible conflicting activities in earthwork operations. If planned productivity varies time progression due to variation in soil characteristics or site access points along the road projects, there is a chance of overlapping or confliction between activities with different productivity. The following section describes the detailed derivation of mathematical formula for the identification of conflicts between two earthwork activities.

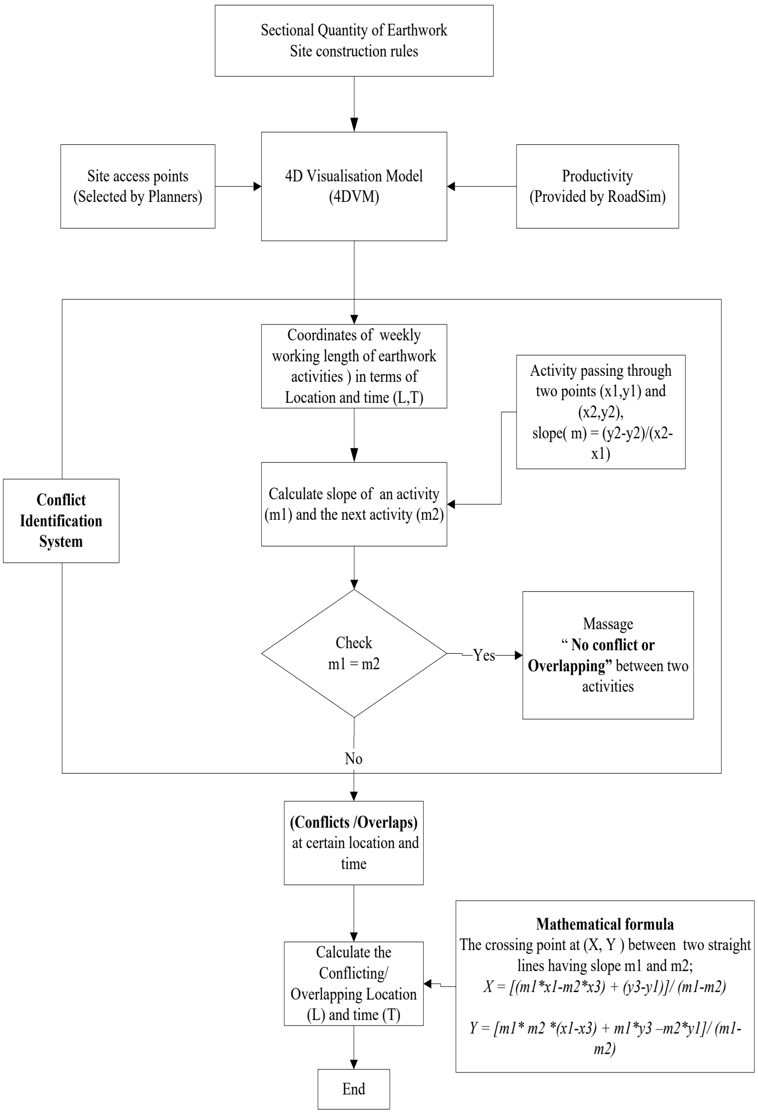


Figure 2: Data flow diagram of Conflicting Identification System (CIS)

2.2.3 *Derivation of mathematical formula for conflicting location and time:*

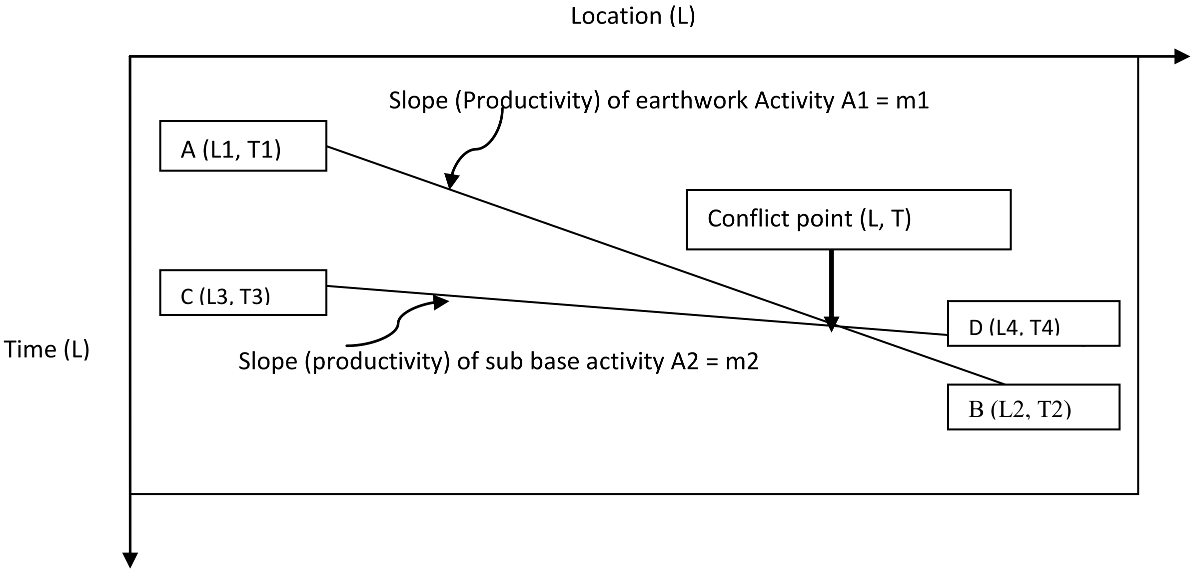


Figure 3: Time Location Chart for earthwork activities A1 and A2

Considering figure 3 for determining the conflicting/overlapping point between activity A1 and A2:
Assume, Line AB represents earthwork activity (A1) which is passing through point A (L1, T1) and B (L2, T2), and Slope of the line AB is represented by m1 . Similarly, Line CD represents sub base activity (A2) which is passing through point C (L3, T3) and D (L4, T4), and Slope of the line CD is represented by m2

Slope of line AB (activity A1) = $m1 = (T2-T1) / (L2-L1)$ ……….. (1)
i.e.; Productivity of earthwork activity A1 is expressed in linear metre/week
Similarly, Slope of line CD (activity A2) = $m2 = (T4-T3) / (L4-L3)$ …….. (2)
i.e.; Productivity of earthwork activity A2 is expressed in linear metre/week whereas; C1 and C2 are the intercept of line AB (activity A1) and CD (activity A2)

According to coordinate geometry, Eq. of a straight line passing through point (x, y) and having slope (m) and intercept c is $y = m x + c$. Similarly, equation of a straight line AB having
Slope (m1), intercept C1 and passing through point (L1, T1) is expressed in equation 1 below
$T1 = m1*L1+C1$ ……………. (3)
Equation 3 is derived by algebraic transformation of equation 1;
$C1 = T1- m1*L1$ ………… (4)
If the line AB is passing through a point (L, T), the equation of the line AB as below: $T = m1* L + C1$ ………… (5)
Substituting the value of C1 in Eq. 3;
$T = m1 *L + T1 - m1*L1$;
Or, $T = m1 *(L - L1) + T1$ ……….. (6)
Similarly, Equation 7 can obtain after deriving, equation of line CD having slope (m2) and passing through (L3, T4) is;
$T = m2 *(L-L3) + T3$ …… (7)
Equations 8 and 9 can be obtained by solving above equations 4 and 7 for identification of conflicting/overlapping location at distance (L) and Time (T)
$L = [(m1*L1-m2*L3) + (T3-T1)]/ (m1-m2)$ ……………….. (8)
$T = [m1* m2 *(L1-L3) + m1*T3 -m2*T1]/ (m1-m2)$ ……….. (9)

Therefore, equation 8 will provide the location where two activities overlap each other and equation 9 will provide a time when both activities overlap each other at the conflicting location.

3. DEMONSTRATION OF THE PROTOTYPE MODEL

3.1 Case study development:

A real life case study involving 1.5 km of road section of lot no. 3 road project in Portugal was selected and demonstrated the model for earthwork activity of cut to fill or spoil. For this purpose, actual road design parameters and geometric data of the L - section and the X-section is considered, and the sectional quantity of earthwork is calculated assuming the typical trapezoidal sections at 25 m intervals along the selected length of road section. The maximum point of cut/fill section is identified where construction operations start first as per existing practice and construction site knowledge. The height is calculated using equation no 2 which is designed, developed and validated by Shah et al (2008).

In this case, Progress height is presented by Z- coordinate whereas the X direction represents along the road and the Y direction represents along the cross section. The road surface is presented in terms of height in mesh form. The productivity of the selected activity is the key variable to identify the next surfaces/layers in the construction progress. The next surface/road profile has been developed based on remaining sectional quantity after progress of earthwork equivalent to the weekly production rate. The operations repeats for the next economical stretch of length where the cutting and filling operations take place in order to generate earthwork progress profiles automatically of a road section. The economical stretch (balance line) has been identified using the mass haul diagram rules and it is used in the model.

3.2 Graphical representation of the VCM:

The terrain surfaces of road profiles generated on a weekly basis throughout the construction period of earthwork operation in the road project depend on the available productivity of earthwork. The terrain surfaces generated by the model of earthwork construction operations in the road project on the weekly basis are presented in figures 4 and 5.

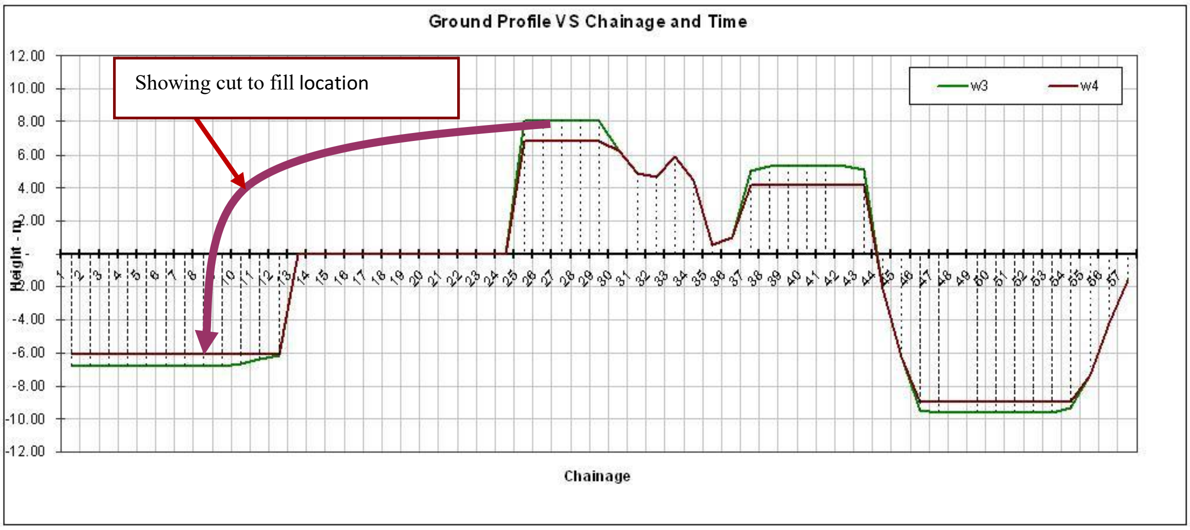
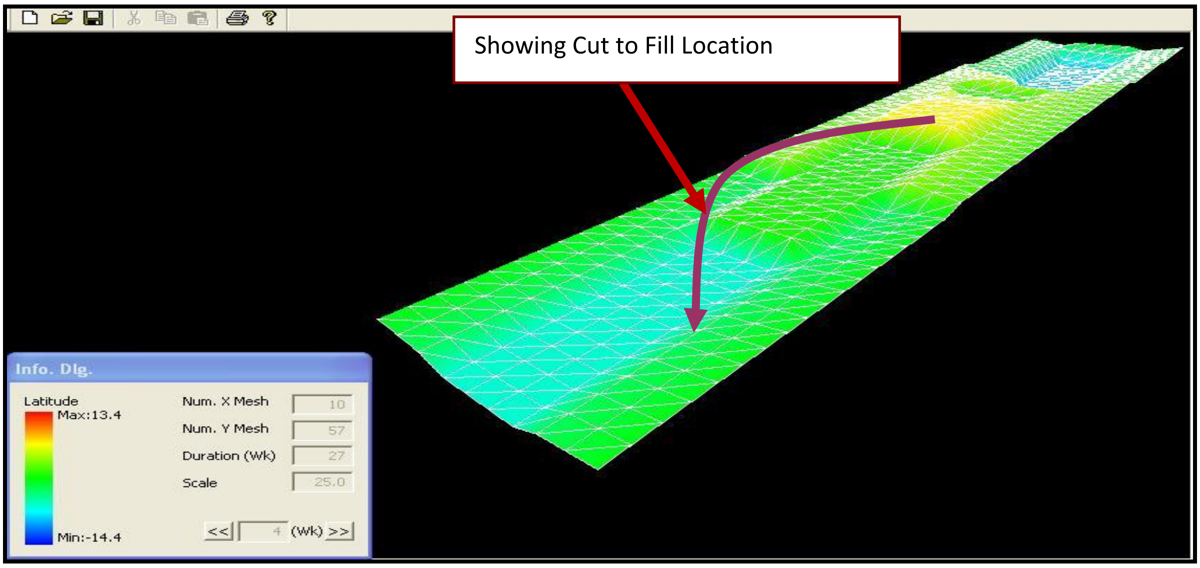


Figure 4 shows the terrain surfaces of road profiles generated at weeks 3 & 4 and location of transforming the earthwork quantity from the cutting to filling section.



Num. X Mesh 10
Num. Y Mesh 57
Duration (Wk) 27
Scale 25.0
4 (Wk)

Figure 5: shows a virtual terrain surface of the road progress profiles generated by the model at the end of week 4.

The figures 4 and 5 are the representation of earthwork scheduling information in order to communicate the optimum allocation of weekly earthwork quantities between cut and fill sections of a road project. The colour index shows the depth of filling and height of cutting of a particular week. The earthwork quantities allocation could be changed according to site access points for required resources and equipment by simulating with “what if scenarios” for different alternative route and soil characteristics along the road section so that site productivity can be improved and the production cost of earthwork can be reduced.

3.2 Weekly Cost Histogram Generated by the VCM:

The developed VCM has additional capability to generate weekly production cost profiles at each chainage (station number) along a road section throughout the earthwork construction operations. Using the real life case study as described above, the generated cost profile is presented in figure 6. The generated production cost profiles is integrated with productivity data of earthwork activity. Any variation in productivity data due to soil characteristics, selection of equipment types, site constrains along the road section have dynamic impact on production cost profiles that assists the planner to control the cost and manage cost budget during planning and construction stage of road projects.

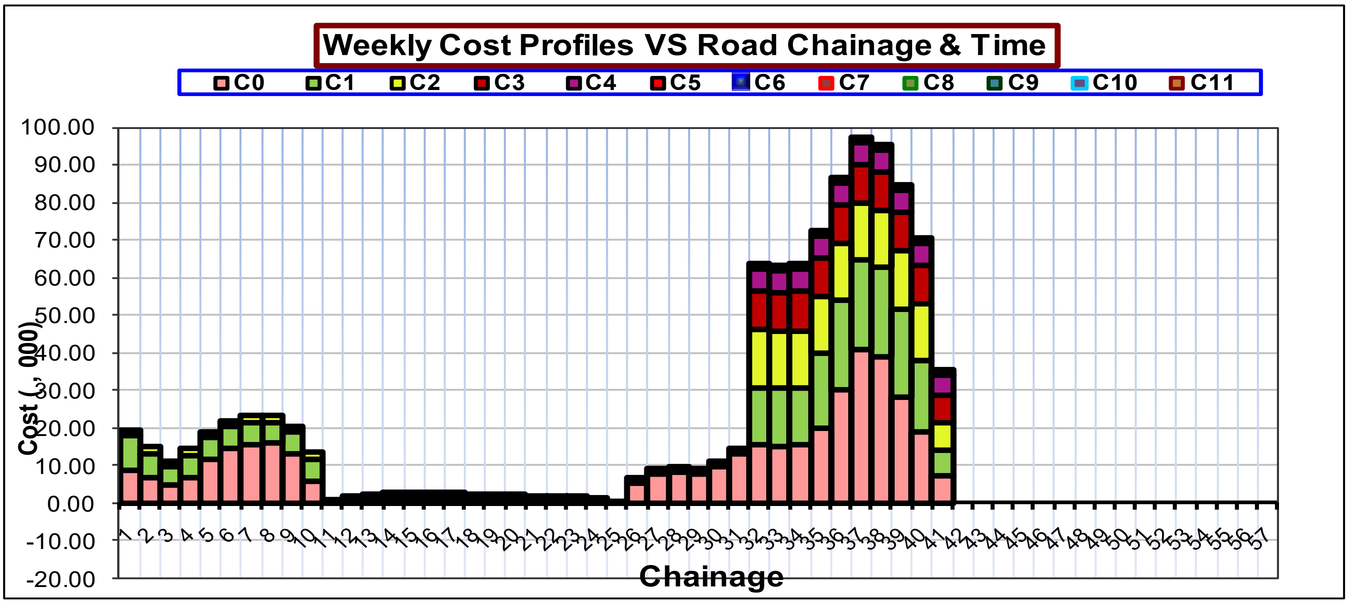


Figure 6: Snap shot of automatic generated weekly cost histogram.

3.3 Time Location Chart (plan) Generated by the VCM:

The developed VCM has additional capability to generate a time location chart as a construction planning and scheduling tool for a road section throughout the earthwork construction operations as shown in figure 7. The time location chart is produced by designing an algorithm and integrating it with the output of VCM: coordinates of starting and ending location with corresponding time in week of earthwork activities.

The number of weeks required for a cutting or filling section is represented by week numbers such as w1f (filling at week 1), w1c (cutting at week 1) and so on as shown in the index. The coordinate of starting and ending station of activity is also presented in terms of location and time (m, wk) as shown in figure 7.

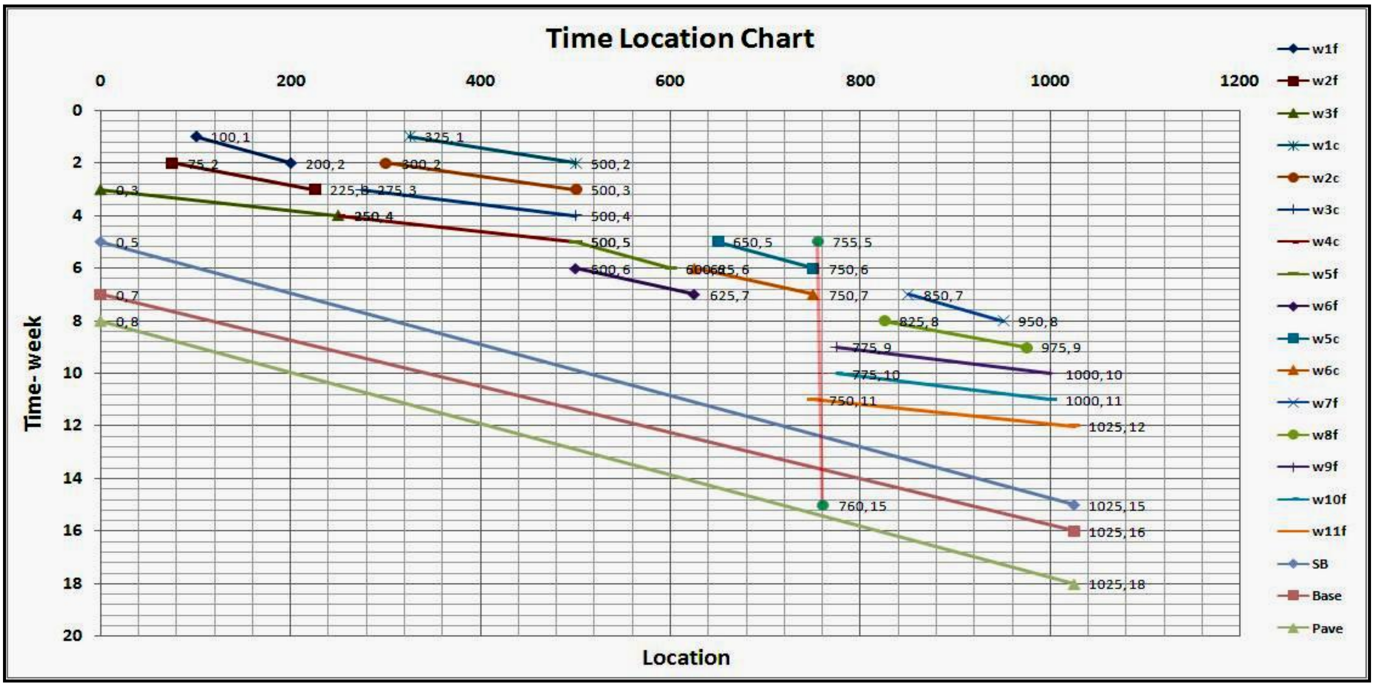


Figure 7: Snap shot of automatic generated Time location chart for earthwork activity.

The generated time location chart is integrated with variable productivity data of earthwork activity. Any variation in productivity data due to soil characteristics, selection of equipment types, site constrains along the road section have dynamic impact on time location construction plan that assists the planner to control the progress and monitor production cost during planning and construction stage of road projects.

3.4 Demonstration of conflict points calculation:

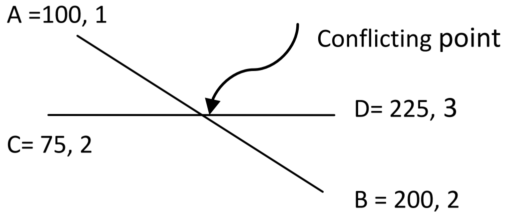


Figure 8: Two typical work activity having different productivity

Assume, line AB represents earthwork activity (A1) of earthwork at week 1 which is passing through starting point A (100 m, 1wk) and ending at point B (200 m, 2 wk). similarly, line CD represents sub base activity (A2) of earthwork at week 2 which is passing through starting point C (75 m, 2wk) and ending at point D (225 m, 3 wk) as shown in figure 8 above.

According to the slope of a straight line; $m = y2-y1/x2-x1$. Therefore, Slope of the line AB (activity A1) = m1

$= (T2-T1)/ (L2-L1) = (2-1) / (200-100) = 0.01$ m/wk, Similarly, Slope of the line CD (activity A2) = m2 $= (T4-T3)/ (L4-L3) = (3-2) / (225-75) = 0.0067$ m/wk

Using equation 8, the conflicting point at the location (L) is determined as below;

$L = [(m1*L1 - m2*L3) + (T1-T3)]/ (m1-m2)$
$= [(0.01*100 - 0.00667*75) + (1-2)] / (0.01-0.00667)$
$= 450.04$ m

Furthermore, the conflicting/overlapping after time (T) is determined as below using equation 9.

$T = [m1* m2 *(L1-L3) + m1*T3 -m2*T1]/ (m1-m2)$

$= [0.01*.0667(100-75) + 0.01*2- .00667*1]/(0.01-.00667) = 4.5$ wks

Therefore, the activities A1 and A2 will conflict or overlap at point (L, T) = (450 m, 4.5 wks)

FURTHER STUDY

In future, the VCM will be integrated with UC/Win Road to enrich the visualisation capability of whole road projects in a virtual environment including surrounding topography. Furthermore, a module will be developed to communicate generated weekly surfaces of progress profiles information with other programme through LandXML format.

CONCLUSIONS

The paper has introduced an innovative methodology for the development of a prototype of VCM to visualise earthwork construction process and a time location plan throughout the earthwork construction operations.

The developed model is useful to generate terrain surfaces according to variable productivity data and at a particular time considering it 4th dimensions, derived from the productivity of earthwork activities. This is considered as an innovative approach for VCM of earthwork process in comparison to 4DCAD technology where variation of earthwork productivity due to site conditions and soil characteristics was not integrated with 4DCAD models.

The model generates visual representation of construction progress, weekly cost profiles, and a time location chart of construction project for earthwork activities. The model has capability in interfacing with user-defined variables including variable productivity data and site access points according to topographical constraints, which is considered as the key achievement of this research study. The model assists project planners and construction managers to analyse “what-if scenarios” with soil characteristics and resource constraint through the visual simulation in construction scheduling and resource planning processes.

The paper concludes that the VCM introduced by the research is practical for earthwork construction management. The model will facilitate a logical decision-making process for construction scheduling and resources planning tasks in improving site productivity and reducing the production cost of earthwork operations in road projects.

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