A VIRTUAL CONSTRUCTION MODEL OF 4D PLANNING IN ROAD PROJECT

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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 road construction industry.

Visualisation technologies have potential to improve communications and coordination amongst the project stakeholders and to optimise onsite productivity through visual simulation of construction process and innovative planning approach. This research study introduces a framework of a 4D planning model for automatic generation of earthwork progress profiles and production cost profiles of a road section, and visualisation of the construction process throughout earthwork operations. The framework is designed and developed by integrating road design data, quantities of cut and fill sections, variable productivity data, algorithms for modelling terrain, and a road profile visualiser. The research details the model to recognise the framework outlined above and it generates progress profiles, cost histogram and a time location plan automatically for the earthwork activity. The model is validated with a real life case study in a road project and was found that the model to be beneficial in generating the terrain surfaces of progress, weekly cost profiles and a time location plan during the construction operations. The model is incorporated with the “variable” productivity data and soil characteristics for analysing with “what if” scenarios. The 4D planning model should assist to project planners and construction managers in producing efficient construction scheduling and resource planning.

Keywords: earthwork planning, 4D planning model, time location plan, productivity, visualisation.

INTRODUCTION

Since the construction industry has unique characteristics, construction managers are under pressure to improve site productivity and reduce production cost. As a result, they require innovative techniques to assist them in producing accurate planning tasks such as scheduling, resource allocation and cost optimisation. The current planning, scheduling and controlling practices in the construction industry are in need of substantial enhancement in quality and efficiency.

Retik *et al.* (1990) explored the potential application of computer graphics to construction scheduling to represent the schedule of construction progress in terms of graphical images at any date. Visualisation was recognised as one of the most

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important tools for achieving this goal. Williams (1996) designed a demand-driven 4D model for the generation of a graphical construction plan based on simulation, visualisation and communication. In a large-scale project, a visual representation of the schedule can be extended to monitoring not only construction progress, but also all the auxiliary activities, including onsite plant and equipment (Adjei-Kumi *et al.*, 1996).

Similarly, McKinney *et al.* (1998) demonstrated the capability of 4D-CAD models to identify construction problems prior to their actual occurrence. Andrej, Branko and Danijel (1999) introduced a new level of support to engineers throughout the product life cycle in order to deal with a platform independent language for 3D visualisation and product modelling using roads as an example.

The failure of traditional techniques such as bar charts and the critical path method (CPM) to provide the information pertaining to the spatial aspects of a construction project have motivated the research effort to incorporate visualisation into project scheduling and progress control (Koo and Fischer, 2000). Zhang *et al.* (2000) further developed a 3D visualisation model with schedule data at the level of construction components. Kamat and Martinez (2001) presented a 3D visualisation model depicting the entire process of a typical construction activity. Dawood *et al.* (2002) developed an integrated database to act as information resource base for 4D/Virtual Reality construction process simulation. The work has been applied to a building project in the UK. Kamat and Martinez (2003) described a general-purpose visualisation system that can generate accurate 3D objects of construction operations and the resulting products. Dawood *et al.* (2005) introduced innovative visual planning tools aiming to assist construction planners to make accurate and informed planning decisions of the spatial aspect of activity during the execution of construction projects and concluded that the visual planning tools need to be practical and communicative.

As discussed above, several research efforts can find in the visualisation of the construction process applied to building construction projects, however, there have been limited research studies in the area of infrastructure construction projects. 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 construction schedule for the intermediate stages of the construction process neglected. Castro and Dawood (2005) developed the “RoadSim” simulator, which is a construction site knowledge-based construction simulation system. It is applicable to produce a master construction schedule in a road project based on simulated productivity of road activities considering with available resources including different sets of equipment and site working conditions. Kang *et al.* (2008) suggested an approach to simulate 4DCAD 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 model developed in 3DCAD environment at a fixed productivity of earthwork activities at different stages during construction operations and linked it with construction schedule.

It concludes that previous research efforts did not integrate the “variable production rate”, which always depends on resource availability and site conditions for the development of 4DCAD model. The key issue faced in road construction site is 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 designing and developing a new system, called 4D planning model (4DPM). The model is integrated with the "variable production rate" of earthwork activity throughout road construction operations.

This paper introduces an innovative methodology for the development of 4D planning model that consist of 4D modelling and automatic generation of a time location plan for the earthwork construction processes in road construction projects. The model generates 3D terrain surfaces of road profiles automatically at the intermediate stages during the earthwork operations. The model is intended 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 introduces a conceptual framework and details of the prototype.

FRAMEWORK OF A 4D PLANNING MODEL (4DPM)

The general specification of framework of a prototype of 4D planning model is outlined in figure 1. The framework integrates road design data, sectional quantities of cut and fill, productivity models, algorithms for terrain modelling and a road 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 4D planning model.

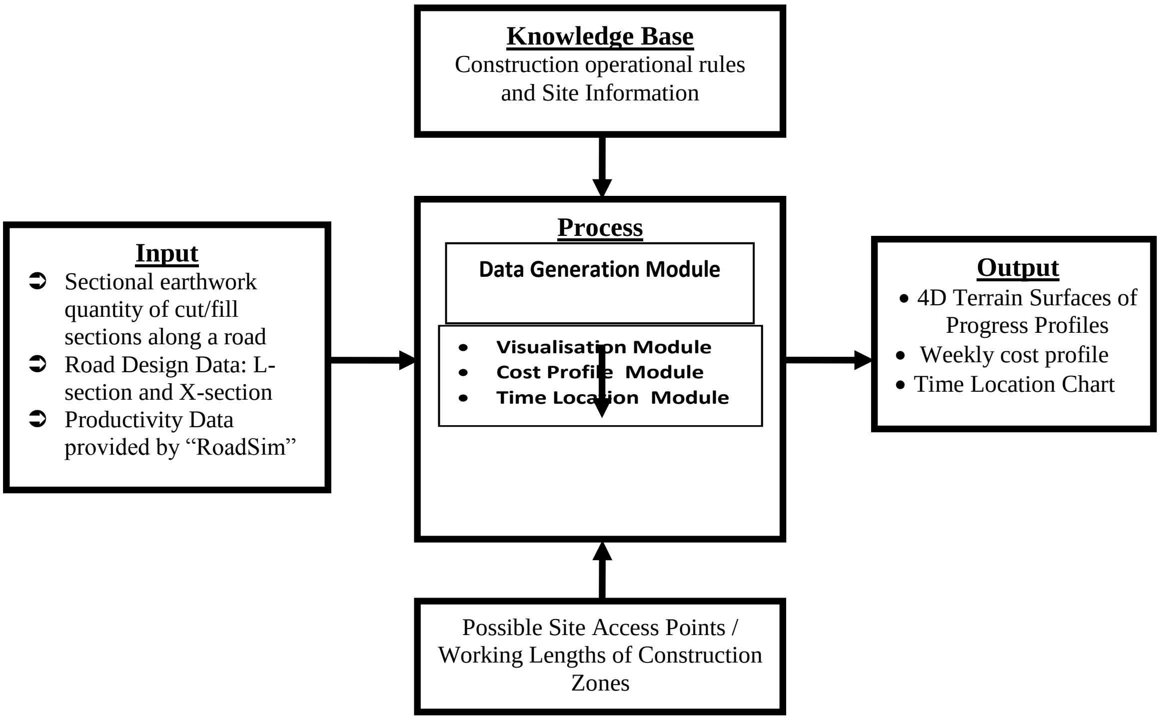

Figure 1 Framework specification of a 4D planning model (4DPM)

Input

The sectional quantities of cut/fill of earthwork activity along a road section, productivity of the activity 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 of the earthwork activity, which is produced by the “RoadSim” simulator, is a key input of the model. This is based on 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 was incorporated within the “RoadSim” simulator

Additionally, the construction knowledge base assists in identifying the possible location and numbers of site access points, methods of construction for different types of soils, selection of equipment set for a particular activity and soil characteristics. The site operational knowledge base assists in establishing sequential relationships amongst listed activities during the construction operations. The following section describes and demonstrates the process of a detailed schedule development including the information flow diagram.

Process

The process of the framework includes four modules: data generation module and visualisation module, a cost profile module and a time location module. The data 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 coordinate data generation are presented in the following sections.

Coordinate data generation algorithms

In this section, a set of algorithms has been developed to automate the generation of terrains of earthwork activities at different stages of the construction process. This depends on quadratic equations, which determine progress for earthwork activity. A flow diagram of the arithmetical algorithms, which use for the calculation of weekly coordinate data of terrain surfaces, is presented in figure 2.

Figure 2 describes the sequences for the height calculation of cutting and filling sections using the algorithms presented in Equations 2 and 3. According to the construction site knowledge base, the top section of cut/fill section is first selected to start the excavation operation and excavate horizontally at the rate of production based on available resources is considered in the study. The remaining volume profile at the excavated section along the road is determined by reducing the rate of production for the specified period, for example daily or weekly.

The flow diagram shows that main initial inputs are sectional quantities of earthwork at each station along a road section. Productivity produced by the “RoadSim” knowledge base simulator is used to calculate the duration of earthwork activity. The site access points are another key input in the selection of a working length of a road section. After selecting a working length, Vmax (maximum volume) is identified by the data generation module and it is considered as a starting point for excavation or backfill processes. Progress will continue in both directions from the identified Vmax station to satisfy the weekly productivity. Vr (remaining quantity) of the selected stations is determined after progressing of week one and the Vr is considered as working quantities for the next week. The number of stations within working lengths is selected by algorithms to satisfy the weekly productivity and achieve weekly-targeted quantity.

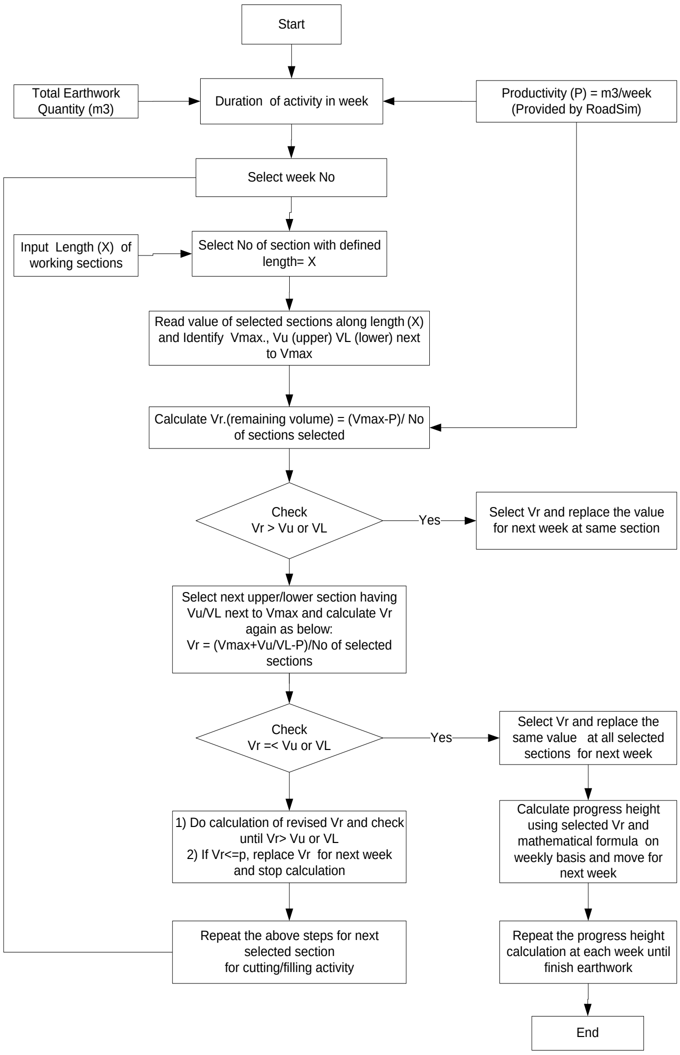

Figure 2 Flow diagrams of coordinate data generation algorithms.

Similarly, after calculating the remaining volume at the selection section, the progress height at the remaining sections is determined using equations 2 or 3, depending upon the type of road cross-sections. This process is repeated to achieve the final design level of the road section shown in L-profiles of the road. The production rate determines the duration of the selected sections. Similarly, the next working section of cutting and filling is selected, considering optimal allocation of soil mass and the process repeats until the completion of the earthwork operations. The following section describes the details of the derivation of the mathematical formula for the calculation of height in the earthwork construction process.

Development of visualisation model

In order to generate the terrain surfaces of road profiles throughout the construction operation in a road project, a typical earthwork activity that includes from cut to fill sections or spoil at the dumpsite is proposed to demonstrate the model and visualise the automatic-generated road surface profiles. The terrain surfaces are the combination of the 3D (2D plus height) of terrain surfaces and time, which is derived from productivity data, is considered as the 4th dimension in the 4D model.

The visualisation engine has been developed using programming language: visual C++ and DirectX. The input of the visualisation engine is the weekly coordinate data generated by the data generation module using innovative methodologies based on the mathematical model, and the generated data is saved as a text file. The x coordinate is considered as length along L- section and y coordinate along width of the along X-section of the road. The origin is considered at (0, 0). The Z-coordinate of the model is considered as the height of the road surface profiles on the weekly basis. The scale used to develop the visualisation model is different for each x, y and z- axis. For the X -axis, the length of load is presented in 1:25, the Y-axis in 1: 10 where width of road is presented, and the Z-axis is presented as 1: 1 for the altitude of the terrain surface. The changes in height of progress that is linked with the productivity of the activity show the realisation of surface changes in a visual image of the terrain profiles of the road. The visualisation model has a capability to render the surface in both solid and mesh format. The following section describes a real life case study the demonstration of the developed 4D planning model.

DEMONSTRATION OF THE 4D PLANNING MODEL (4DPM)

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 was discussed and derived by Shah *et al.* (2008).

In this case, the height is presented as Z- coordinate whereas at X direction is along the road and the Y direction is 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 can be developed based on remaining sectional quantity after progress of earthwork equivalent to the weekly production rate. The operations are repeated for the next economical stretch of length where the cutting and filling operations take place and profiles is generated automatically for the rest of the road length.

Graphical Representation of Road Profiles generated by the 4DPM

The terrain surface of road profiles that are generated on a weekly basis throughout the construction period of earthwork operation in the road project were based on the available productivity of earthwork. The virtual terrain surfaces generated by the model of earthwork construction operations in the road project on the weekly basis are presented in figures 3 and 4.

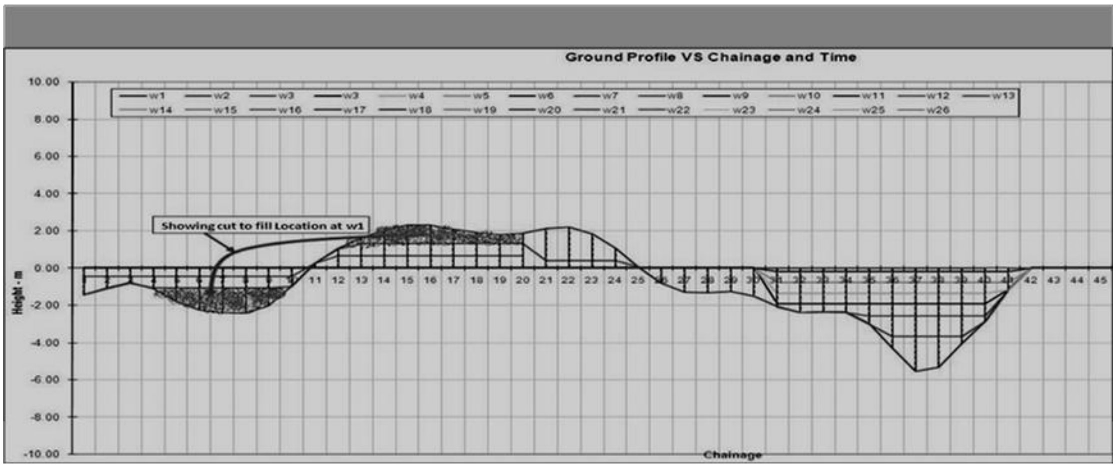

Figure 3 shows road progress profiles generated during earthwork operations and location of transforming the earthwork quantity from the cutting to filling section.

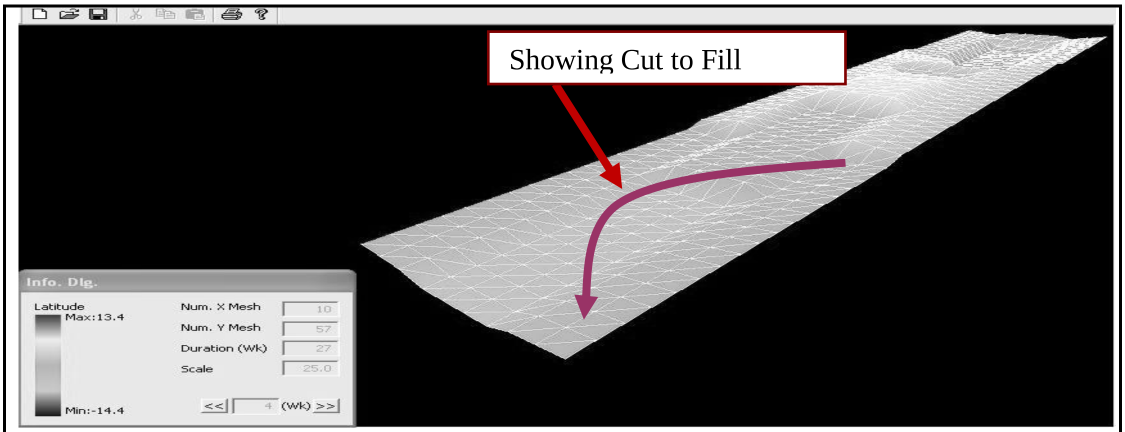

Figure 4 shows a virtual terrain surface of the road progress profile generated by the model at the end of week 4.

The figures 3 and 4 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.

Weekly Cost Histogram generated by the 4DPM

The developed 4D planning model has the 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 5. The generated production cost profiles are integrated with the productivity data of the earthwork activity. Any variation in productivity data due to soil characteristics, selection of equipment types and site constraints along the road section have the dynamic impact on the production cost profiles that assists the planner to control and manage budget cost during the planning and construction stages of road projects.

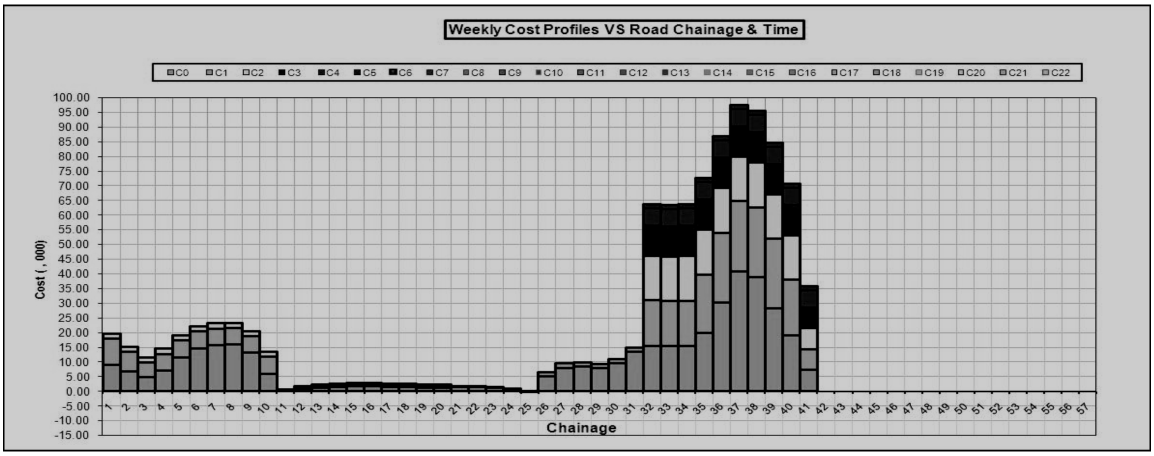

Figure 5 Snap shot of automatic generated weekly cost histogram.

Time Location Chart (plan) generated by the 4D Model:

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

Using a real life case study as described above, the automatic generated time location chart/plan is presented in figure 6. 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 represented in terms of location and time (m, wk) as shown in figure 6.

The automatic generated time location plan has capability to integrate with "variable productivity data" of earthwork activity. Any variation in the 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. Automatic generated time location plan is shown in figure 6 below.

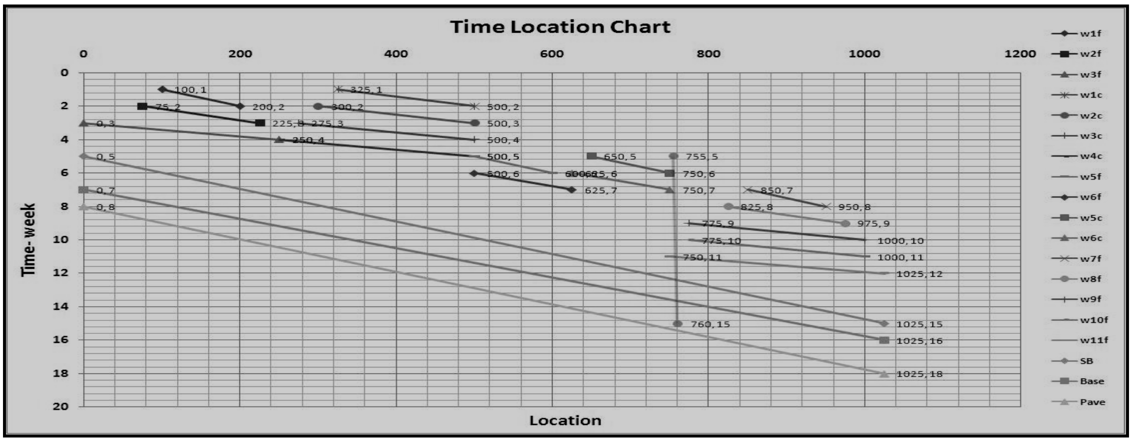

Figure 6 shows the automatic generated time location plan in a road project.

Further study

In future, the 4D planning model 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.

CONCLUSION

The paper has introduced an innovative methodology for the development of a prototype of 4D planning model to visualise earthwork construction process throughout 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 4D modelling of earthwork process in comparison to 4DCAD technology where variation of earthwork productivity due to the lack of integration functionalities with site conditions and soil characteristics with the existing 4DCAD models.

The model generates visual representation of construction progress, weekly cost profiles and a time location chart of construction plan 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 the 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 4D planning model 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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