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Shah, RK, Dawood, N and Castro, S (2008) Automatic generation of progress profiles for eathwork operations using 4D visualisation model. Electronic Journal of Information Technology in Construction, 13. pp. 491-456. ISSN 1874-4753

AUTOMATIC GENERATION OF PROGRESS PROFILES FOR EARTHWORK OPERATIONS USING 4D VISUALISATION MODEL

SUBMITTED: January 2008
REVISED: September 2008
PUBLISHED: October 2008
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SUMMARY: *Despite of the advances in construction planning and scheduling software, construction managers and planners are still facing problems in achieving accurate planning, scheduling and costing due to the one-off nature of the construction projects and the inherently uncertain site conditions and soil characteristics. The aim of the research presented in this paper is to introduce a new methodology for integration of 'variable productivity' data with a visualisation model of earthwork operations. To achieve this aim, a number of objectives have been set: identification of current industrial practices and confirming the needs and aspirations of the industry, designing of a methodology and a model to integrated variable productivity with visualisation, and performing a case study to demonstrate and verify the model. The paper presents a prototype of a 4D visualisation model which is designed by integrating the road design data, quantities of cut and fill, productivity model, algorithms for modelling terrain surfaces and a progress profile visualiser. The model generates automatically terrain surfaces of progress profiles for earthwork operations and visualises progress profiles throughout the construction operations under different site and soil conditions. It is demonstrated with a real life case study in a road project. The paper concludes that the model should be able to assist in producing efficient construction scheduling and resource planning, thereby reducing production cost and improving on-site productivity.*

KEYWORDS: *earthwork progress profiles, terrain surface generation, variable productivity, 4D visualisation model.*

1. INTRODUCTION

Constructing a civil engineering infrastructure project of any magnitude has become more challenging task than ever due to the highly competitive environment and complexity of the management process. The continuously evolving construction methods and techniques stipulate the need for innovative tools that can assist project managers/planners to plan and manage construction projects more efficiently. Visualisation was recognised as one of the most important tools for achieving this purpose (Construct IT 1997). The failure of traditional techniques such as bar charts and the critical path method to provide the information pertaining to spatial aspects of a construction project have motivated the research effort to incorporate visualisation into project scheduling and progress control (Koo and Fischer 2000). Retik (1997) highlighted that visual simulation of a construction process might assist a planner in a better perception of a project and in the integration of other parties' activities in the planning process. A visual representation of the schedule can be extended to monitoring not only the construction progress, but also improves communication on site including plant and equipment management (Adjei-Kumi et al. 1996).

Several research efforts (McKinney et al. 1996, 1998; Adjei-Kumi and Retik 1997; Tibault et al. 1999; Zhang et al. 2000) have been conducted in the visualisation of construction process related to construction planning and scheduling. Dawood et al (2002) developed an integrated database to act as information resource base for 4D/VR construction process simulation and evaluated through a building project. Kamat and Martinez (2003) have introduced a general purpose visualisation system for simulation which is independent of CAD software. Dawood et al (2005) introduced an innovative visual planning tool aiming to assist construction planner to make accurate and informed planning decisions of the spatial aspects of activities during the execution period and found that the visual planning tools are practical and communicative in building projects.

However, limited research projects are found in earthwork planning, scheduling and visualisation of infrastructure construction projects. Askew et al (2002) have developed an approach to automate the earthwork planning process to create activity sets using a knowledge base and a simulation of earthwork processes. Hassanein and Moselhi (2004) have developed an object-oriented model to plan and schedule highways operations. The model generates the work breakdown structure and automatically develops the precedence network respecting job logic. Tam et al (2007) proposed a method to automate the earthmoving planning by integrating a path- finding algorithm, a plant selection system, compatibility and genetic algorithms to optimize the alternatives in terms of costs, productivity, safety and environmental consideration.

In addition to the above, Liapi (2003) has focused on the use of visualisation during the construction phase of highway projects, to facilitate collaborative decision making on construction scheduling and traffic planning. However, the visualisation of schedules at the intermediate stages of the construction process has been neglected. Castro and Dawood (2005) have developed the "RoadSim" simulator, which is a construction site knowledge base driven construction simulation system. It can be used to develop a master construction schedule in a road project based on simulated productivity of road activities under available resource with different sets of equipment and site working conditions but neglects the visualisation of the construction process.

Kang et al (2006) suggested an approach to simulate 4D models for the movement of earthwork activities 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 model of earthwork operations was produced in a 3D CAD model at equal volume and fixed production rate of activities at different stages during construction operations and linked with time. Platt (2007) identified that the continuity of earthwork activities did not work with predetermined object simulation associated with 4DCAD technology and suggested that dividing the earthwork into discrete objects would be a possible solution. However, he did not address how to divide the earthwork into discrete objects and recommended that a new approach is necessary to overcome this problem for modelling of earthwork operations.

None of the above research efforts did address the interface of "*variable productivity*" with a 4D model. The key issue faced on a construction site is "variable productivity" from one day to another because of the unique characteristics of the road construction industry such as variation in topography and soil types along the road, daily weather, site working conditions, resource constraints and other unpredictable factors. To overcome these issues, in this paper a new methodology for the development of a *4D visualisation model* (4DVM) of earthwork operations and integration of "variable productivity" with 4DVM is suggested. A prototype of 4DVM is designed based on 3D terrain surfaces that are generated automatically using coordinate data and linked with the time, which is derived from the productivity data of earthwork activities representing the 4th dimension of the 4D model. The new methodology and functions presented in the paper are innovative work compared to current 4D CAD systems which are focused on building projects. The integration of "*variable productivity*" with the 4D visualisation model of earthwork operations is the main focus of the research presented in this paper. The proposed model will assist the construction managers and planners to produce efficient construction schedules and resource plans so that projects can be delivered on time and cost.

The remainder of this paper is organized as follow. Section 2 presents the findings of a construction industry survey that was carried out to identify existing practices and problems facing the construction industries in planning and scheduling processes and possible application of visualisation technology for earthwork operations in road construction, and to outline a specification for a 4D prototype of earthwork activities. Section 3 presents the development of the prototype of the 4D visualisation model that includes inputs, process and output of the model. Section 4 presents a case study demonstration and user interaction with the model. Conclusions of the paper are presented in the last section 5.

2. EVALUATION OF CONSTRUCTION INDUSTRY SURVEY

The aim of the performed industry survey was (1) to identify current practices in the construction planning and scheduling process, construction methods, software being used, critical factors affecting the productivity, application of visualisation technology in earthwork operations, and (2) to synthesise the industrial requirements of 4D modelling during earthwork operations. The semi-structured interview was used on a questionnaire that was designed for the purpose of the survey.

The questionnaire has been categorised into four sub sections: (1) background information of participated companies, (2) existing practices, (3) problems faced in planning and scheduling, and (4) factors affecting for earthwork operations. Each section was designed with aim of understanding the relationship that may exist in practice for earthwork planning, scheduling and visualisation of the construction process. The responses are vital and represent the existing practices currently being used in UK based road construction and/or civil engineering projects. The findings from the survey are described in the following sub sections.

2.1. Background information of the participated companies

The survey was targeted to the infrastructure construction companies based in the UK, aiming to summarise the views and opinions of the construction and planning professionals involved in construction planning, scheduling and visualisation of construction processes. The survey continues and aims to achieve a target of 30 construction companies. Overall 60% responses have been received from the construction companies and are included in this paper for data analysis and presentation of the survey results.

The responses from the participated companies provide vital information regarding existing practices and technology being used in the infrastructure construction projects. Figures 1(a) and (b) present the types and values of construction projects in which the participated companies in the survey have been involved.

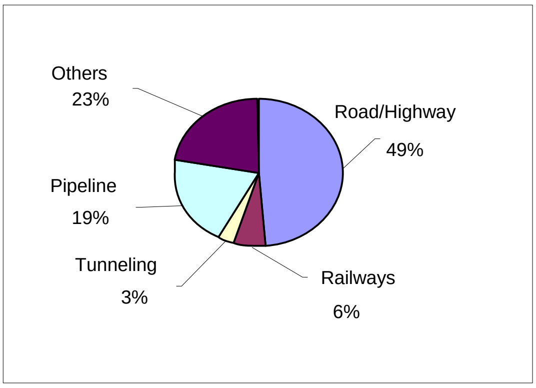

FIG. 1(a): Types of projects in which the companies in the survey have been involved.

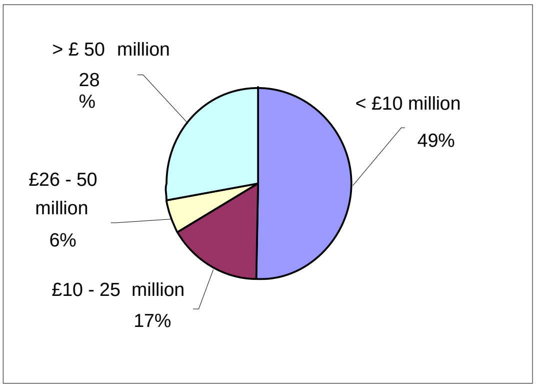

FIG. 1(b): Type of project value involved by the participated companies in the survey.

Participants were asked questions regarding existing practices and software being used in construction sites, existing problems faced in the planning and scheduling for earthwork operations and critical factors affecting the earthwork planning and operations at construction site. Responses from the participants are analysed and presented in the following sections.

2.2. Existing practice in earthwork operations

The survey results suggested that the majority of companies are using previous experience of their professionals and intuitive methods for the planning and scheduling process. Fig. 2 (a) presents the survey result that 73% of the construction companies use their past experience, 9% intuitive methods, 9% rule of thumb rules and the rest use other techniques. Similarly, 73% are still using traditional mass haul diagrams whilst 20% use past experience and the rest 7% use commercial software for earthwork planning as shown in Fig. 2(b). The survey concludes that there are no existing practices for visual simulation tools in the earthwork planning and simulation with "what – if" scenarios considering different site conditions. However, the survey exposed that there are problems facing construction companies in planning and scheduling of earthwork operations which are discussed in the next section.

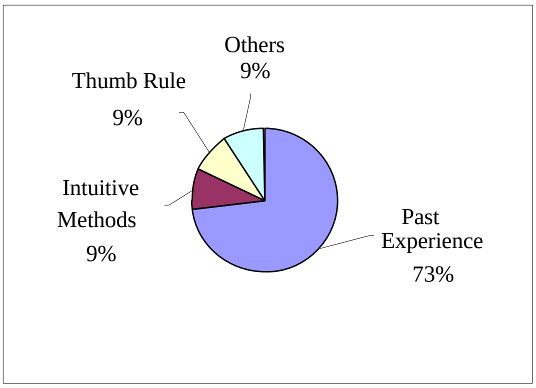

FIG. 2(a): Existing practices for earthwork planning and scheduling.

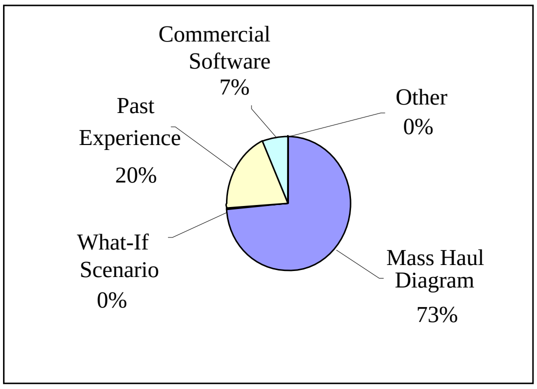

FIG. 2(b): Existing techniques used for earthwork planning.

2.3. Existing problems in the planning and scheduling process

Respondents were asked to rank common problems facing construction companies in earthwork planning and scheduling tasks. The survey exposed that poor construction plans, relation with utilities services and change orders of work scope by clients are the major factors contributing to the delay of construction projects. However, incorrect design and equipment breakdown also contribute minor delays. The survey identified that 29 % of all projects were delayed due to poor construction planning and scheduling (Fig. 3).

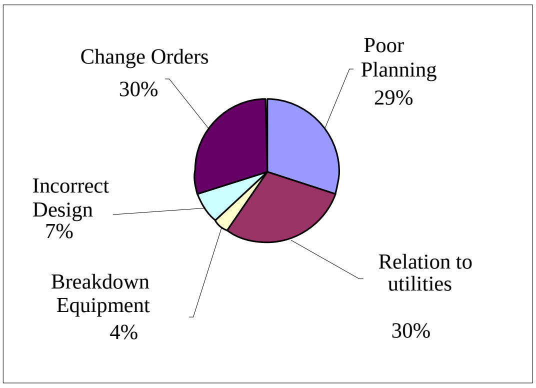

FIG. 3: Factors responsible for the delay of earthwork construction projects.

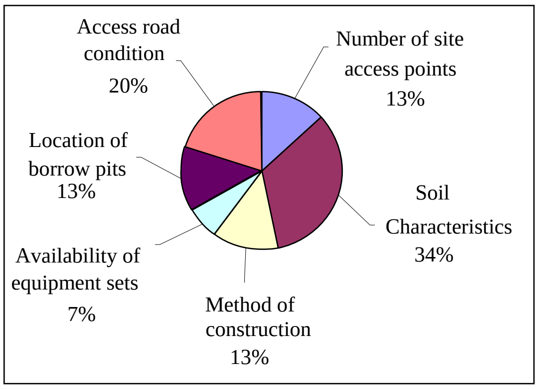

FIG. 4: Critical factors affecting earthwork operations.

2.4. Critical factors affecting the earthwork operations

The respondents were asked to rank the factors that are considered during earthwork operations. They expressed their views that soil characteristics are the most critical factors that affect the earthwork planning followed by access road conditions, number of access points, location of borrow pits, method of construction used and availability of equipment respectively, as shown in Fig. 4 above.

Since the respondents were experienced planning and construction professionals, the authors believe that the information and opinion provided by them will be reliable and valid particularly in the UK construction industry. Therefore, considering the problems faced by construction companies and the critical factors affecting earthwork planning, in this paper a prototype of a 4D visualisation model of earthwork operations using a new methodology is proposed. The following section details the components of the prototype.

3. PROTOTYPE OF THE DEVELOPED 4D VISUALISATION MODEL OF EARTHWORK OPERATIONS

A general specification of the developed prototype of 4D visualisation model (4DVM) is shown in Fig. 5. It answers the findings of the survey which includes planner past experience, poor planning and lack of visual planning system as well as critical factors such as soil characteristics, number of site accesses, haulage distance and types of equipment sets that are affecting earthwork planning. The specification of the model is obtained by integrating the road design data, sectional quantities of cut and fill based on L-section and X-section, variable productivity data provided by the "RoadSim" productivity model, algorithms for modelling terrain profiles and a road profiles visualiser. The model assists in generating visual terrain surfaces of road progress profiles throughout the earthwork operations. The next sections describe the input, the computational process and the visual output of the 4DVM.

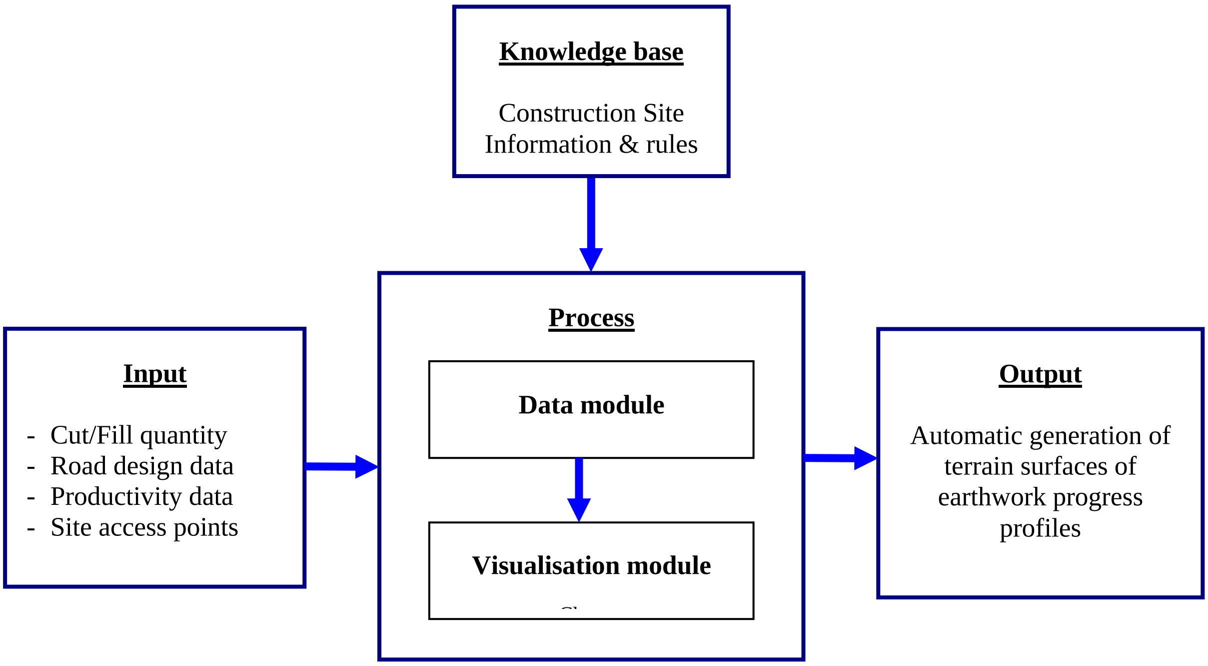

FIG. 5: High-level specification of the prototype for 4D visualisation model.

3.1. Input

The sectional quantities of cut and fill activity, productivity data, site access points and construction site knowledge and rules are the key inputs of the model. The sectional cut and fill quantities are calculated using road design data such as L-section and X-section at required intervals (25m) of chainage in road projects using VBA code embedded in MS Excel. The productivity of earthwork activities is determined using the "RoadSim" system. Soil characteristics along the working road section, types of available equipment sets for a selected activity, haulage distance for moving soil mass, working conditions and all other factors including weather conditions control productivity of the earthwork and these factors have already been incorporated within the "RoadSim" productivity model which is based on the construction rules elicited from construction professionals of road construction projects.

Additionally, construction knowledge and rules provided by project planners or construction managers guide to identify possible locations and numbers of site access points, methods of constructions for different types of soils, selection of equipment sets for a particular activity. The construction knowledge also assists to establish sequential relationships among the listed activities during earthwork construction operations.

3.2. Computational process

The computational process of the 4DVM includes two parts: "data module" and "visualisation module". The "data module" processes input data using VBA programming embedded with Excel and produces coordinate data of terrain surfaces on weekly basis in the assigned sequences of earthwork activities. The details of the data module are described in the following sections 3.2.1, 3.2.2 and 3.2.3. The "visualisation module" processes the coordinate data generated by the "data module" and transforms it into terrain surfaces of road profile in the regular triangular grid by means of a visualiser engine which was developed using C++ and Direct X. The difference of level shows the height of cutting and filling sections in positive and negative numbers respectively. The description of the visualisation module that generates automatically the terrain surfaces of earthwork progress profiles throughout construction operations is provided in section 3.3.

3.2.1. Schedule Development

The flow diagram of schedule development in road construction projects that outlines the main steps of activity together with their logical interactions is presented in Fig. 6 below.

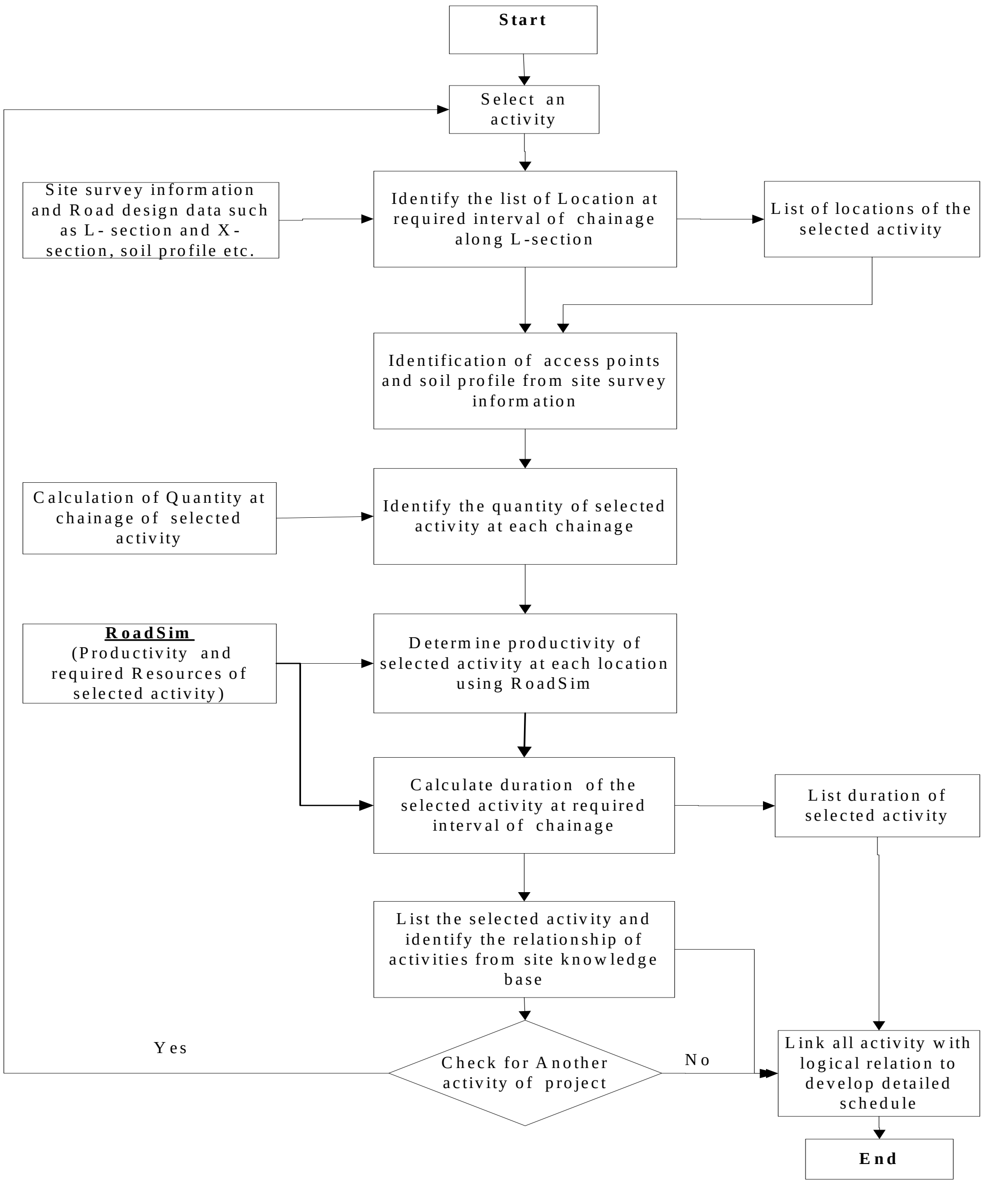

FIG. 6: Flow diagram of schedule development process.

The lists of sections are defined at required intervals along the road using L-section profile. Road design data such as L-section and X-section is used to identify the list of locations as per required intervals and required accuracy. The site survey provides the detailed information regarding site access points, haulage distance and access routes conditions, and location of borrow pits and dumping sites.

The number of site access points is another key factor that affects resource planning and visualisation of construction scheduling information. The sectional quantity is calculated at each and every listed location of road project. The RoadSim system is used to identify productivity information and required resources at selected locations and activities of the road building process. The productivity is used to determine the duration of the selected activities. The process is repeated for other activities of road projects and the precedence relationship is established based on the site construction operational knowledge and rules. The coordinate data generation, which is based on the height calculation of typical road cross-sections of 3D terrain surfaces, is derived from geometrical formulas. This is discussed in the following section.

3.2.2. Derivation of the mathematical formulas

In road construction, the typical cross-sections shown in figures 7 and 8 are most commonly applied and are thus considered to formulate the mathematical formulas for the shapes shown in cases (a) and (b) below. There are also other types of sections that are more rarely used and are therefore not considered in this paper, but will be considered in future research. Furthermore, since rock excavation is a different method than other types of excavation, it is also not considered and is suggested for future research work. The assumption made for the development of the mathematical formulas for cases (a) and (b) together with an illustration is described below.

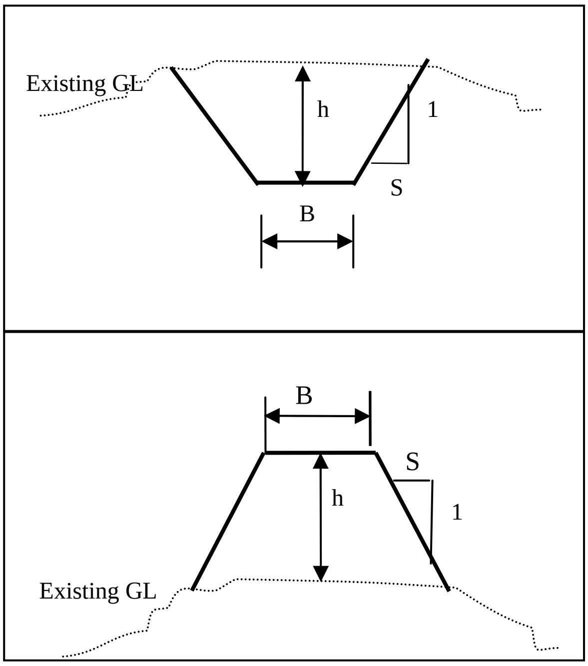

FIG. 7: Typical cross-sections for cutting and filling of road projects for flat terrain surfaces.

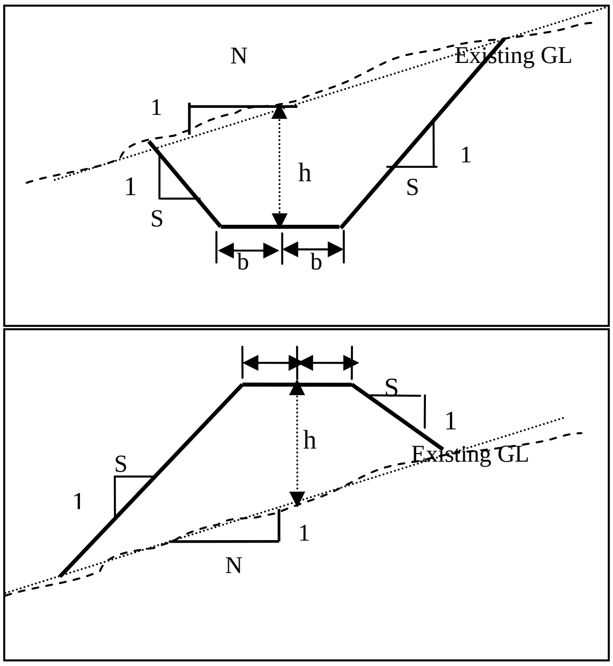

FIG. 8: Typical cross-section of road projects having transverse slope of terrain surfaces.

Case (a): Typical road cross-section, which is mostly used in road projects in flat terrain as shown in Fig. 7

For the derivation of mathematical formulas, the following assumptions are made:

- The road cross-section is considered as trapezoidal shape having side slope S:1
- Ai = cross-sectional area of trapezoidal at section i = $Bh_i + Sh_i^2$
- i = number of the section, varying from i = 1 to n along the road
- S = side slope.
- B = design width of the road

- h = height between exiting ground level and design level at a road section
- V_i = volume of earthwork for cut/fill at section i
- L = the length between two sections.

Using the common formula for sectional area calculation:

$$A_i = \frac{V_i}{L}$$

$$Sh_i^2 + Bh_i + (-\frac{Vi}{L}) = 0 \qquad (1)$$

The height of the cross-section shown in Fig. 7 can be determined as follows:

$$h_i = \frac{-B \pm \sqrt{B^2 + \frac{4SVi}{L}}}{2S} \qquad (2)$$

Case (b): Typical road cross-section, which is most commonly used for uneven terrain surface having transverse slope as shown in Fig. 8

Equation (3) is used to determine the height of the cross-section shown in Fig. 8. It is derived in the same manner as equation (2) for the cross-section shown on Fig. 7 above and is expressed as follows:

$$h_i = -b \pm \left[(\frac{1}{SN}) \sqrt{(\frac{V_i S}{L}) \times (1 - \frac{S^2}{N^2})} \right] \qquad (3)$$

where,

- h_i = height of the cross-section at section i
- i = number of the section, varying from i = 1 to n along the road
- N = transverse slope of existing ground Horizontal: Vertical (N:1)
- S = side slope of cross-section Horizontal: Vertical (S:1)
- b = half width of the road section
- Vi = volume of mass earthwork cut/fill at cross-section i
- L = the length between two section.

3.2.3. Coordinate Data Generation

The flow diagram of the programming algorithms for the calculation of the coordinate data of terrain surfaces on weekly basis is shown in Fig. 9 below. The maximum cutting or filling points along the road are identified where construction operations start at first using the construction site knowledge provided by planners. In the diagram, Vmax indicates the maximum volume of cut or fill sections along the road, Vr is the volume of the remainder at the cut/fill sections after progressing of the earthwork at particular periods, Vu is the upper limit and VL is the lower limit of the volume of a road section, and p is the cut/fill productivity at the section where the earthwork progresses.

The mathematical formulas shown in equations (2) and (3) have been derived using the quadratic equation principle and are used to determine the progress for earthwork activities in a road project based on the assumptions made for cases (a) and (b). These formulas assist to determine the progress of earthwork operations in terms of sectional height. The details of the stepwise process during the calculation of progress heights at cut and fill sections are described below.

At first, the highest point of cutting sections and the lowest point of filling sections are selected as start locations for excavation and backfill operations. According to construction knowledge rules, the cutting and filling operations are performed layer by layer in horizontal direction at the rate of equipment productivity within available resources throughout the construction operations. The sectional volume at each section along the road is determined by reducing the excavated or backfilled quantity on weekly basis. The height of the remaining section is identified using equation (2) or (3). The process is repeated until the final design level of the road section is achieved. The production rate determines the duration of construction operations for the selected road section. A road project is required to breakdown into max 1.5 km sections to satisfy the limitation of the developed model during the construction operations.

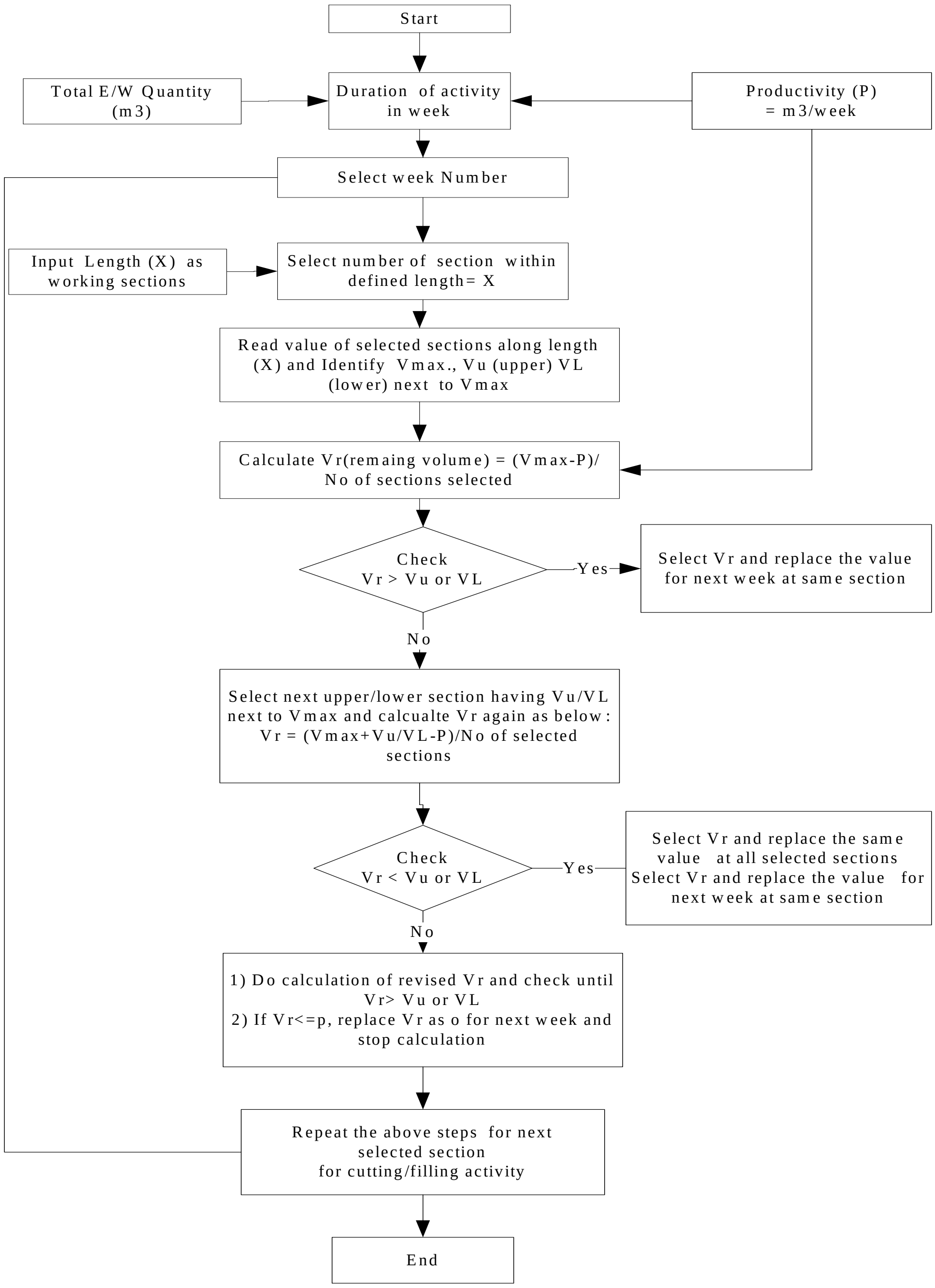

FIG. 9: Flow diagram of the programming algorithms for generation of coordinate data for terrain surfaces.

3.3. Visualisation

Visualisation, comprising the second part of the computational process, is used to generate the terrain surfaces of earthwork progress profiles throughout the construction operation in a road project. This includes cut to fill sections or spoil at dump site to visualise the construction process. The 4DVM of terrain surface is based on a 3D representation of the surface, linked with the time derived from the productivity data of the earthwork activity.

The "visualisation module", which encompasses a visualisation engine for 3D modelling for terrain surfaces, has been developed using Visual C^{++} and Direct X. The input of the "visualisation module" is the coordinate data which is produced by the "data module" using innovative methodologies based on the mathematical algorithms and saved as a text file. The changes in height of progress that, linked with variable productivity, show the realisation of surface changes of the road profiles are presented as a visual image. The visualisation model is capable to render the surface in both solid and mesh format.

The output of the model comprises automatically generated visual images of terrain surfaces of road profiles throughout the earthwork operations. The model assists project planners and managers to visualise and analyse the impacts in the earthwork construction plan and schedule by rehearsing with "what-if" scenarios for "variable productivity" data and selecting the alternate site access points for different site conditions and soil characteristics along road construction projects.

4. CASE STUDY

A real life case study involving a 1.5 km of road section of Lot No. 3 of a road project in Portugal was selected to demonstrate and verify the developed prototype. Since the actual excavation operations are executed at small sections generally from 1 to 1.5 km sections of construction length, the developed 4D model is limited for the construction length of 1 to 1.5 km road section. Therefore, a 1.5 km of road section was selected for demonstration of the model. Actual road design parameters and geometric design data such as L-section and X-section were considered and the sectional quantity of earthwork was calculated assuming typical sections at 25 m intervals along the road project. The height is calculated using equation (2). The detailed description of the user interaction and the output of the model are presented in sections 4.2, 4.3 and 4.4. Section 4.5 describes the mapping of the construction business process where the functionalities of 4DVM should be applied. An example for the calculation of the road cross-sectional height is shown below.

4.1. Illustration of height calculation

For an example, typical data is selected from Lot No. 3 of the road project in Portugal between chainage 0+025 ~ 0+050:

Volume (V_i) = - 2834.70 m3 ($\pm$ sign shows the cutting and filling volume)
Side slopes S:1 = 1.5:1
Width of Road (B) = 26.1 m
Chainage interval (L) = 25 m

Using equation (2):

$$\text{Height } (h_i) = \frac{-B \pm \sqrt{B^2 + \frac{4SV_i}{L}}}{2S} \tag{4}$$

In the above equation (4), only positive sign is considered as feasible value for this case.

$$h_i = \frac{-26.1 + \sqrt{(26.1)^2 + \frac{4*1.5*2834.70}{25}}}{2*1.5} = -8.39$$

Here the negative value of height shows the height of a filling section, and a positive value shows the height of a cutting section.

The X and Y coordinates are considered as road length along L-section and road width along X-section. The origin is assumed at (0, 0). The Z-coordinate is considered as the height of road profiles. The scale used to develop 3D terrain surfaces is different for the X, Y and Z axes. The length of the road is presented on the X-axis in 1:25 scale, the width of the road is presented on the Y-axis in 1: 10 scale, and the height of terrain surfaces is presented on the Z-axis in 1: 1 scale, assuming the design level of the road as base line.

The road surface is presented in terms of height in the mesh format. Productivity data produced by "RoadSim" has been used to identify the next surface during earthwork progress. The next surface of the earthwork progress profile is identified by subtracting the progress of earthwork equivalent to the weekly productivity data from the remaining sectional quantity. The operations are repeated for the next construction length where the cutting and filling operations take place and generates automatically earthwork progress profiles for the rest of the road project.

4.2. User interaction with 4DVM

A screenshot of the prototype user interface is presented in Fig 10. The interface corresponds to the contents of the "data module" and the "visualisation module". The 4DVM includes five sub modules: "DataGeneration", "DataExport", "4DModel (RoadViz)", "Filling productivity" and "Cutting productivity". They are activated by button commands used for various purposes. The details of each module are described below.

The filling and cutting productivity modules are used first to determine the productivity for cutting and filling activities with the help of the "RoadSim" productivity module as shown on Fig. 11. The "DataGeneration" module is used to generate automatically weekly coordinate data of progress profiles of earthwork throughout the construction operations by processing the input data (variable productivity, sectional quantity of cuts and fills sections and site access points) provided by project planners. Based on an arithmetic algorithm developed during the research, it is realised using VBA programming and is embedded in the MS Excel platform. The "DataExport" module is used to filter the necessary data and export that in the form of a text file to the "visualisation module" where the data is processed to develop terrain surfaces of earthwork progress throughout the construction operations. The "4DModel (RoadViz)" is used to process the exported data and to generate automatically weekly surfaces of progress profiles for the earthwork operations. The processes are repeated for each 1.5 km section to complete the earthwork operation of the road construction project because the developed 4DVM is limited to 1.5 km road sections. The model enables identifying the starting locations and construction length of earthwork operations for different types of ground profiles at different topography and soil characteristics.

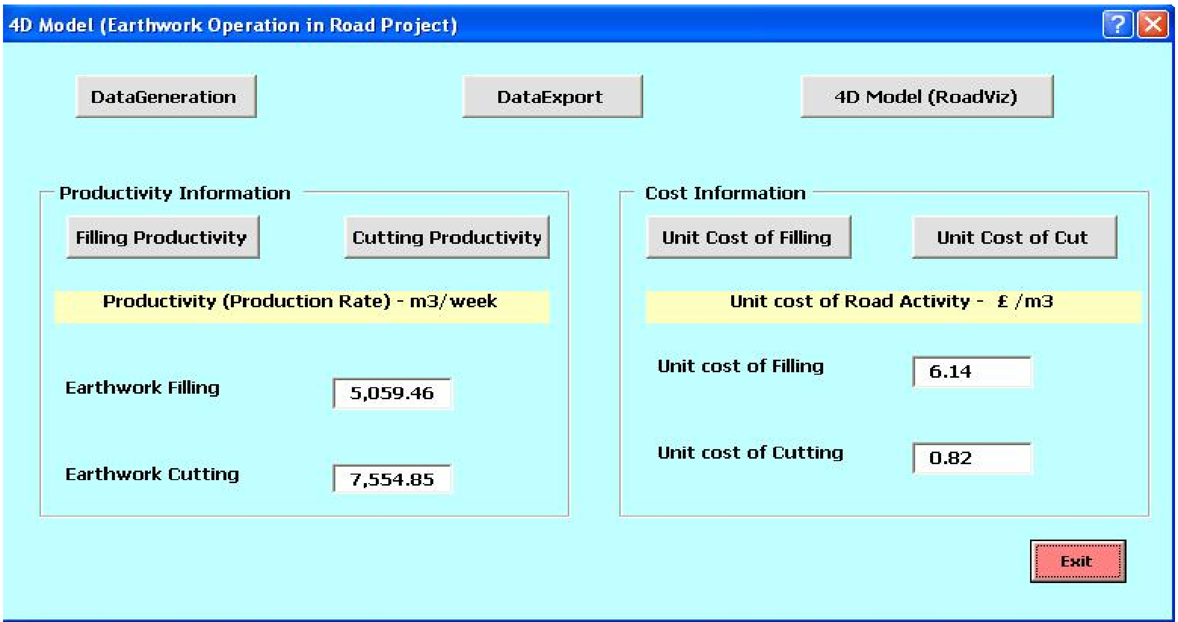

FIG. 10: Screenshot of the prototype user interface for the data generation module of earthwork operations.

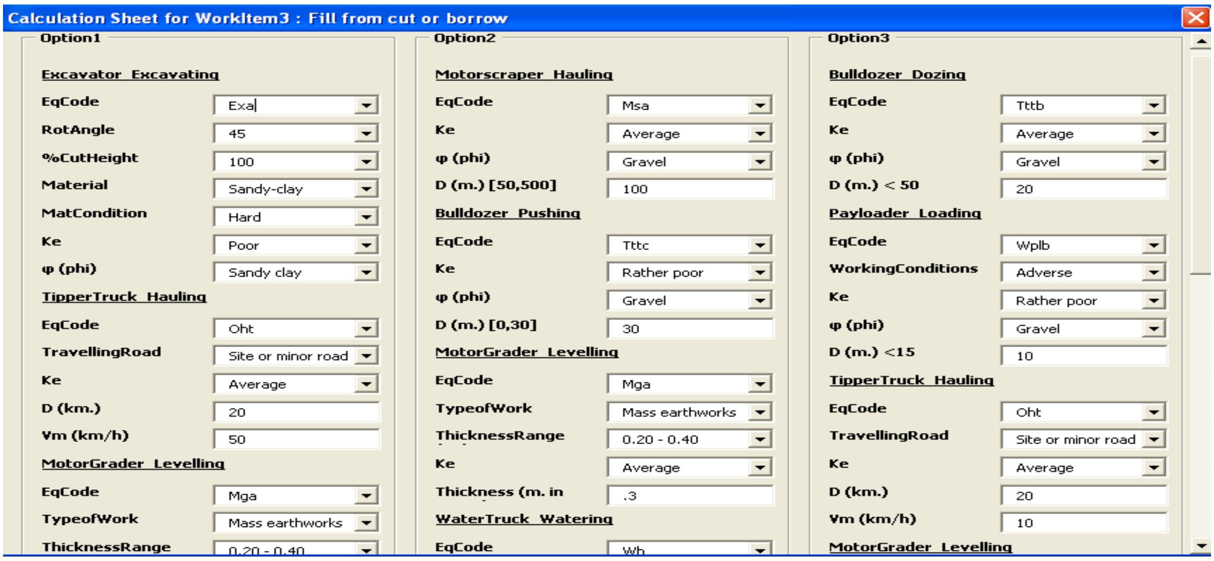

FIG. 11: Productivity module of "RoadSim" determining the productivity of earthwork activities. (Depicted from Castro and Dawood, 2005)

4.3. Generated earthwork progress profile for variable productivity

After processing the inputs as explained in the above sections, the outputs of the model are presented in the form of visual images. Figures 12 (a), (b) and (c) show the automatically generated earthwork progress profiles of the road section at the end of week five (W5) in comparison with the initial ground profile at week (w0) for three sets of productivity data. A total of 22 weeks is required to complete the selected road section based on the productivity data produced by the RoadSim system under the available resource and site constraints. The weekly generated progress profiles by the 4D visualisation model for productivity data (pc) for cutting, and productivity data (pf) for filling sections, are presented for minimum, average and maximum scenarios in figures 12 (a), (b) and (c) respectively.

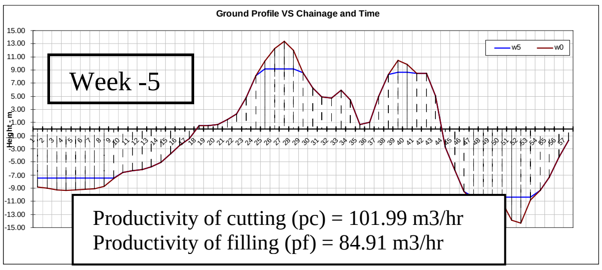

FIG. 12 (a): Progress profiles of earthwork operations at minimum productivity.

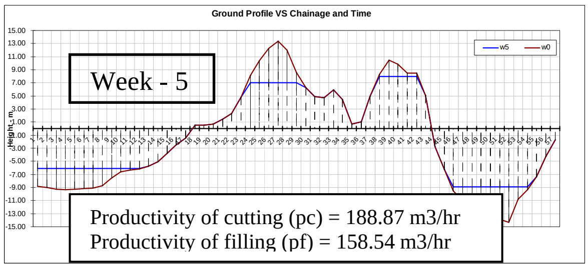

FIG. 12 (b): Progress profiles of earthwork operations at average productivity.

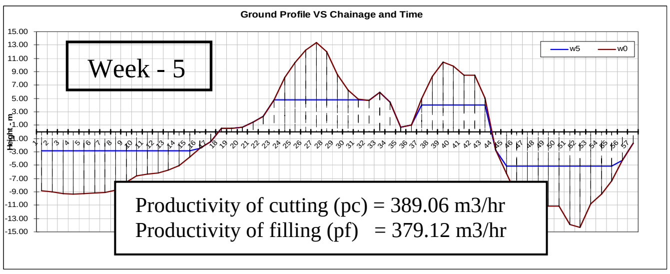

FIG. 12 (c): Progress profiles for earthwork operations at maximum productivity.

4.4. Generated terrain surface of earthwork progress for variable productivity

The graphical images of road surface progress profiles, which have been generated automatically by the model during construction operations on weekly basis, are presented in figures 13(a), 13(b), 14(a), and 14(b).

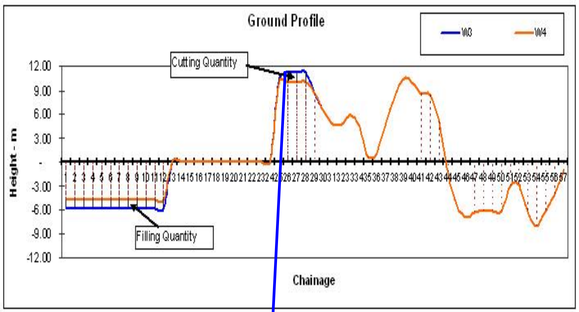

FIG. 13 (a): Graphical images of the road profiles generated by the model at weeks 3 & 4 and location of the transformed cutting and filling earthwork during construction operations at the end of week 4.

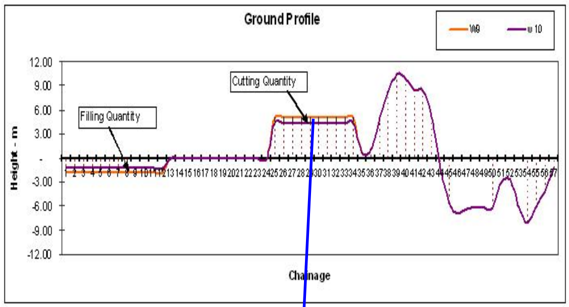

FIG. 14 (a): Graphical images of the road profiles generated by the model at weeks 9 & 10 and location of the transformed cutting and filling earthwork during construction operations at the end of week 10.

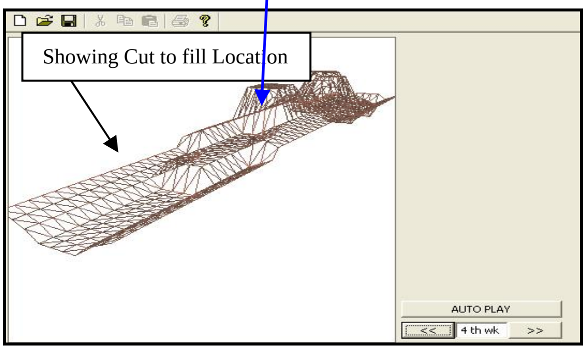

FIG.13 (b): Screenshot of the graphical image of the terrain surface of the earthwork progress profile generated by the model at the end of week 4.

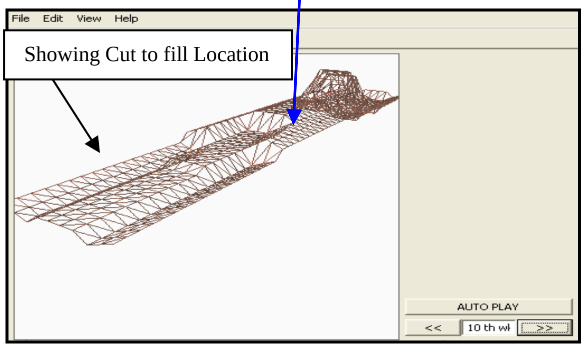

FIG. 14 (b): Screenshot of the graphical image of the terrain surface of the earthwork progress profile generated by the model at the end of week 10.

Fig. 13 (a) shows the graphical images of the progress profile generated at weeks 3 & 4 and the location of transformed cutting and filling earthwork during construction operations at the end of week 4. Fig. 13 (b) shows the graphical image of the terrain surface of the earthwork progress profile generated by the 4DVM at the end of week 4.

Similarly, Fig. 14 (a) shows the image of terrain surfaces of the road progress profile generated by the developed model at weeks 9 & 10 and the location of transformed cutting and filling earthwork during construction operations at the end of week 10, and Fig. 14 (b) shows a graphical image of the terrain surface of the earthwork progress profile generated by the 4DVM at the end of week 10.

4.5. Mapping the 4DVM functionality in the construction business process

This section describes the mapping of the construction business process so that the functionality of 4DVM can be applied. The process mapping was produced based on the information captured during the review of a construction company. For confidential reasons the name of the company cannot be revealed here and will be referred to as 'company A'. Planning directors and engineers of the company have been interviewed and a detailed business process map has been developed. Fig 15 below shows the outline of the business process. It is composed of two main sub-processes: (1) bidding process, and (2) detailed planning process. The bidding process is the first stage of any new project and includes the preparation of technical and financial proposals. These proposals are prepared based on company preliminary cost estimate, limited site information and initially proposed construction methods within limited resources. The preliminary cost is estimated based on contract documents: Bill of Quantity (BOQ), design drawings and specifications of works and materials.

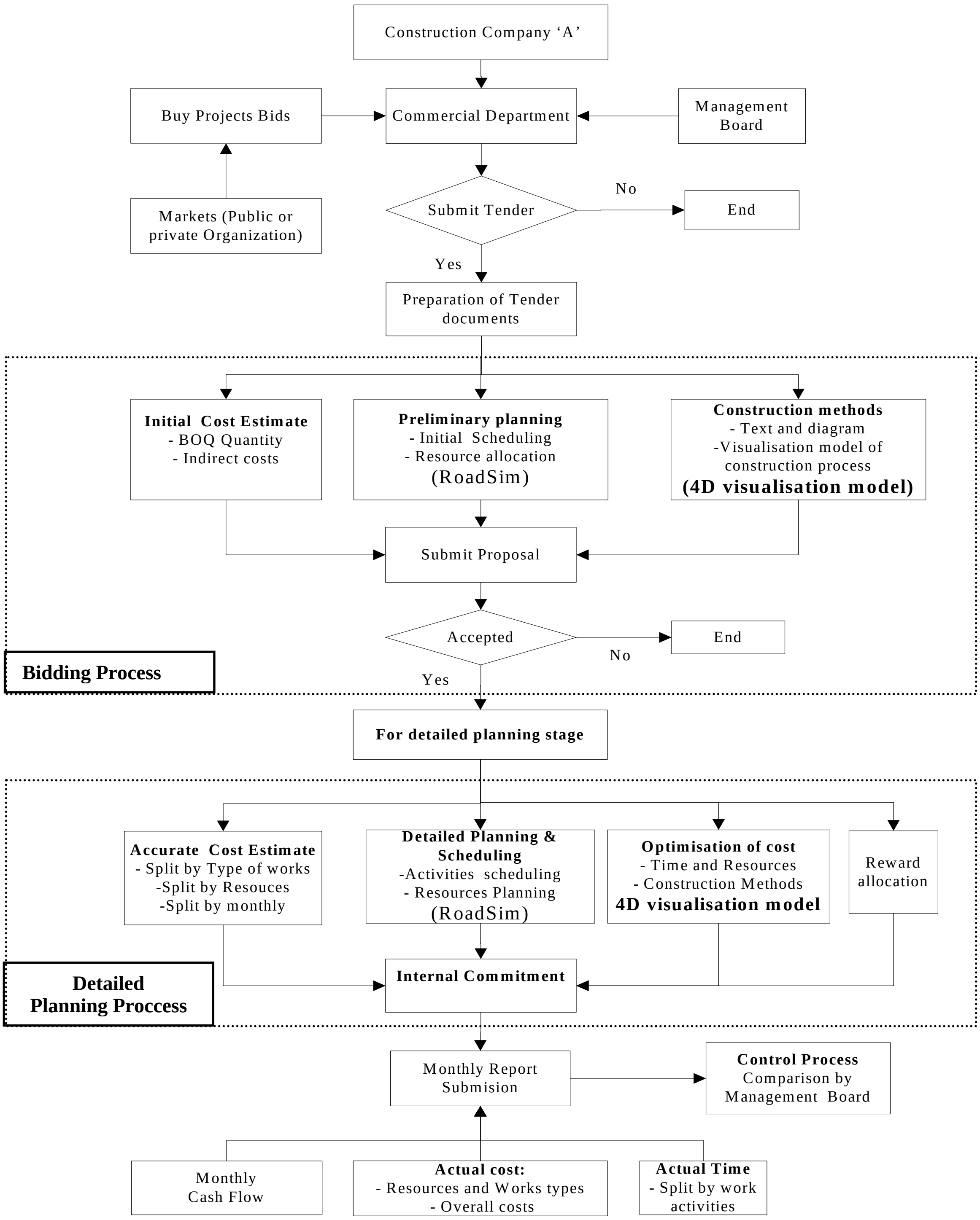

FIG. 15: Mapping of the construction business process of a construction company.

Once the project is confirmed, the detailed planning process will follow. It includes the detailed preparation of accurate estimates which are separated in different levels such as type of works, resources and monthly schedule. Additionally, a detailed schedule is prepared based on work activities and project duration using available resources. Resource planning is the crucial part of the process that impacts the overall project plan. In this stage, the focus is concentrated on the efficient utilization of the resources using company tools in order to deliver the project on time and cost. The control process compares actual with planned progress in terms of time and cost in order to implement corrective actions and keep the construction progress on schedule and within budgeted costs.

The process mapping showed that the 4DVM should be able to assist at the bidding stage to build the confidence of clients by showing virtual construction methods for different site and soil conditions. The model should also be able to assist at the detailed planning stage for resource planning of earthwork operations through the visual simulation of automatically generated earthwork progress profiles by varying the productivity data considering equipment sets and soil characteristics and site access points.

5. CONCLUSIONS

The research presented in this paper has introduced a new methodology to integrate "variable productivity" with the 4D visualisation model for earthwork operations in road projects. A review of current practices and methods used in the construction industry showed that there is an absence of a systematic approach for the earthwork planning process due to the uncertain site conditions and soil characteristics of earthwork operations. Methods used for earthwork planning in the construction industry are subjective, time consuming and heavily dependent on experience and knowledge of the planners. The industry survey revealed that 73% are still using traditional mass haul diagrams whilst 20% use past experience and the rest 7% use commercial software for earthwork planning. The survey also identified that 29 % of all projects were delayed due to poor construction planning and scheduling, and the survey result exposed that soil characteristics are the most critical factors that affect the earthwork planning followed by access road conditions, number of access points, location of borrow pits, method of construction used and availability of equipment.

The paper presented a prototype of a 4D visualisation model which is integrated with "variable productivity" data of earthwork operations which depend on the soil characteristics and site conditions along road projects. The specification of the model has been achieved by integrating the road design data, sectional quantities of cut and fill based on L-section and X-section, variable productivity data, algorithms for modelling terrain profiles and a road profiles visualiser. The model has been demonstrated successfully with a case study in a real road project. This verified that the 4DVM is able to generate automatically earthwork progress profiles and visualise terrain surfaces of progress profiles throughout the construction operations under different site and soil conditions. The integration of "*variable productivity*" with the 4D visualisation model of earthwork operations which has been developed during the research is the key research contribution to knowledge presented in this paper.

The paper concludes that the graphical representation of progress profile surfaces simplifies the interpretation of earthwork operations to planners and allows them to compare earthworks progress under various equipment sets, site conditions, soil characteristics and site access points. The developed 4DVM is a decision support tool which is capable to assist in producing efficient construction scheduling and resource planning, thereby reducing production cost and improving on-site productivity.

6. ACKNOWLEDGEMENTS

The presented research was supported by the Centre for Construction Innovation and Research (CCIR), University of Teesside, UK and Portugal based International Construction Company. Sincere appreciation is given to the sponsor from the authors.

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