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A model for the automated generation of earthwork planning activities

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Abstract: A review of techniques used in industry showed that there is an absence of a formalised, systematic approach to earthworks planning. The techniques used tend to be subjective and time consuming with a heavy reliance given to the experience and knowledge of the planner. This absence of a formalised technique can lead to inaccurate planning and makes explanation of the techniques difficult. This paper describes the development of a new automated approach for use by the planners to generate earthworks activities that overcomes such limitations. As well as creating activity sets in a much shorter time, the ability to compare various sets allows the planner more scope when planning earthworks. The model is able to generate activity sets that are comparable to those generated by a project planner.

Key words: activity generation; construction; earthwork; linear projects; planning

Introduction

In planning construction works the choice of activities is by no means an exact science (Mawdesley *et al.*, 1997), but for an activity to be suitable, it needs to be realistic, achievable, and complete. To achieve this, the planner needs to have an understanding of how the work is carried out. With such knowledge there is less risk of not creating an acceptable activity.

When planning earthworks, the planner is faced with the problem of having to split up the required work into manageable activities. These activities are influenced by many factors, including site layout, plant selection, weather characteristics, and condition of haul road. With an understanding of how these factors affect earthmoving, the planner can create earthworks activities whilst also considering some of the influencing factors. Often, such an understanding is based upon intuition and decisions are made on subconscious thoughts. These are still useful and should not be discounted. During the research project, it was found that planners rely largely on judgement and experience to determine suitable activities. This judgement was found to be based on an understanding of the site characteristics and knowledge of earthmoving operations.

As well as having to split up items of work into activities, earthworks planning has an additional complication. Cut and fill activities have to be paired so that cut activities have corresponding fill activities. This ensures that all material has an origin and destination. The same principle is applied to the use of landfill sites and borrow pits. The choice of

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activity pairs can have an effect on subsequent activity pairings and thus the process of creating earthworks activities is often iterative. This can be extremely time consuming to a planner.

The additional complication of activity pairing is arguably one of the most important and difficult aspects of earthworks planning. Many techniques have been developed (as reviewed in a following section) in attempts to optimise or improve the activity pairing combinations.

Completeness is another important consideration when planning earthworks activities. Checks should be made that all necessary work is included in the plan. Aspects such as internal haul are often overlooked but should be included in the plan of work. Likewise, duplication of work should be avoided.

By examining earthmoving techniques and characteristics, the limitations or inadequacies of planning methods can more easily be highlighted and understood. This will enable the formulation of an earthworks planning model, which will address such limitations.

This paper focuses on the development of a model for earthworks planning. In particular, it describes an automated method for the generation of earthwork activities. A software package based on the developed model has also been developed and used in by a major construction company in the UK. It has been developed as part of the research project, which allows the generation and evaluation of earthworks activities.

Philosophy of earthmoving

Since the start of large-scale modern road construction (after the Second World War), standard approaches and philosophies have been adopted by the construction industry for earthmoving operations. Although certain areas such as plant development have progressed over the years, many of the widely used techniques for earthmoving remain the same. This section examines and discusses the approaches that are commonly used for earthmoving.

The cut-to-fill approach represents the most fundamental idea behind earthmoving. The basic reasoning is to excavate material in areas of cut (cuttings) and deposit material in areas of fill (embankments).

In practice, it is often found that material that is excavated from a cutting can be of a suitable material type for use as fill in an embankment. From this phenomenon stems the basic reasoning of cut-to-fill. By adopting this technique, the movement of material is kept within the site boundaries, (providing the total cut and fill volumes are equal). This reduces the need for excavated material to be exported and deposited off site while new material is being imported to the fill sections. This combining of cut and fill sections is common practice for earthmoving operations.

Such an approach, at construction stage, is relatively straightforward. As a result of this however, the planning of earthworks (adopting the cut-to-fill approach) can be extremely complex. Selection of cut-to-fill pairs can influence the choice of subsequent activities. This results in the possibility of alternative activity sets being created (depending on different patterns of activity selection). Thus the activity selection process can be highly complex. Such a problem is often viewed as being analogous to the ‘Transportation Problem’, (Winston, 1995; Pilcher, 1992).

In practice, the main mathematical technique used as a planning tool at present is the mass haul diagram. This diagram (Figure 1) shows cumulative material volume along a linear project. Positive gradients depict 'cut' and negative gradients 'fill'. By drawing horizontal lines (balance lines) that intersect the mass haul line, equal volumes of cut and fill are shown. These balance lines are the means by which earthworks activities are produced. They are plotted either at specified chainage intervals (e.g., 200 m) or, as is more commonly the case, at locations where the gradient of the mass haul diagram changes (places at which a cut and fill are adjacent).

Modelling earthwork planning

Much work has been done to improve earthworks planning methods. Developments in the use of mass haul diagrams have led to techniques such as linear programming being applied to earthworks planning.

Mayer and Stark (1981) used linear optimisation as a technique to produce earthworks activities. The objective function involved minimising the amount of 'overhaul', that is, minimising movement of material between non-adjacent cut and fill sections.

Easa (1987) used a system known as EARTHN, which was based on a linear programming approach. The model attempted to minimise the cost of earthmoving by minimising haul distance. It was assumed that the unit costs for using borrow pits and landfill sites were non-constant.

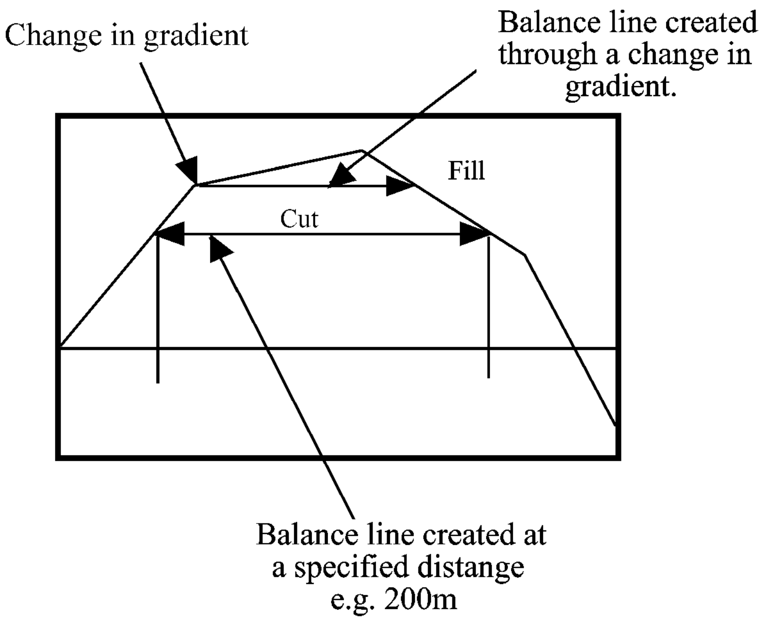

Figure 1. Mass haul graph and balance lines

The software package, MICRO-CYCLONE (Vanegas *et al*., 1993) has been used for earthworks modelling. The simulation package enables the planner to set up an earthworks model and a simulation of plant movements.

Jayawardane and Price (1994) highlighted a new approach that combined linear optimisation, cycle simulation, and network scheduling to produce earthworks activities. The simulation model defines the cut and fill activities by simulating plant movement for all activities. Linear optimisation is used to find the most efficient use of borrow pits and landfills. Network scheduling is used to determine the logic between activities. This system (known as RESCOM) overcomes many of the problems that have arisen in other techniques. It accounts for constraints along the project as well as integrating other non-earthworks activities into the project plan.

More recently Gransberg (1996) proposed a method for optimising haul unit size and number in order to minimize the cost of earthmoving. This was based on the loading characteristics of the equipment and its physical attributes but did not really consider the site layout. Martinez (1998) addressed aspect directly in his work on simulation of earthmoving for planning purposes but did not incorporate the detailed physics of the project. Kannan *et al.* (1997) looked at the project more holistically, bringing the earthmoving in as part of the overall planning and decision-making process on a project.

These research projects have largely focused on optimising a single function (e.g., cost). Other aspects as well as costs have to be considered, including risk, environmental impact, safety, quality, and complexity of construction. Aspects such as access points, state of haul road and plant crossings have an influence on the choice of activities and these influences should be considered when planning and controlling earthworks. An approach is needed that accounts for such an array of factors.

The proposed model

The methodology used in this research is outlined in the following sections. First, it has been necessary to understand the overall procedure followed by current planners in arriving at the proposed construction plan for a road project. Secondly, the way in which planners reach their decisions and the nature of those decisions has been examined. Both of these were accomplished through interviews with project planners and observation of their working methods. As a result of this, ideas for new software to assist the planner are put forward.

The activity generation model used here is based on newly developed idea of activities being in the form of a 'cut-to-fill pair'. A cut-to-fill pair consists of two activities: the excavation of earth and its subsequent placement. Since all excavated material must be placed somewhere, even if it is off-site, all earthworks can be modelled by a cut-to-fill pair. The generation of activities can be divided into four parts:

- Acquisition and formalisation of the data
- Activity generation model
- Calculation of attributes for each activity
- Creation of multiple activity sets.

Earthworks data is displayed by means of a mass haul diagram and activities are shown by means of a time-chainage diagram. The overall objective of the model is to enable the creation of a selection of activity sets that can subsequently be evaluated and compared.

Acquisition and formalisation of the data

The acquisition and formalisation of the data is the starting point of the earthworks planning model. It is the stage where all required data is obtained and transformed into a useable format.

The ability of any model to evaluate activity sets in a reasonable manner will rely heavily on the knowledge used and thus various experts were approached during the knowledge acquisition stage. Planners, estimators and engineers were used in an attempt to obtain as much useful and relevant information as possible.

Previous research has shown that there is no single technique suitable for knowledge acquisition (Sharp and Howard, 1996). Several techniques, including interviews, re-interviewing on an informal basis, shadowing planners, monitoring the use of software, literature reviews, site visits, and analysis of previous projects were used during the research project as a means of gaining information about earthworks planning.

It was found that planners, although they had substantial knowledge about earthworks planning, found it difficult to express their knowledge in a structured manner. It was evident from the interviews that a substantial amount of the knowledge was 'subconscious', see also (Giarratano and Riley, 1994). That is to say, they were not aware of the reasons for an action being carried out. One of the planners expressed the view that '*a general feel is used*...' when creating earthworks activities. Such information was of limited use for developing a knowledge base and thus other techniques had to be used to elicit the knowledge. If a planner could not explain adequately the reasons for a decision or action, subsequent interviews using specific examples were used as a means of obtaining further information.

A systematic approach has been developed to ensure that complete and reasonable data sets are obtained before activity generation is started. Many of the components that make up such approach are currently used in practice as part of earthworks planning. However, the way in which they are used has not been documented or developed in detail. The developed earthworks planning model ensures that such shortfalls are overcome. Figure 2 shows the flow of information for this section of the model.

The data that are required for creating earthworks activities include:

- *Earthworks specification*: details the locations of required cut and fill areas
- *First and second stage work*: has effect on the splitting up of work into activities
- *Shrinkage/bulking rates*: Alters the volumes of available cut.

The developed model accounts for variations in material volumes due to shrinkage and bulking. It also accounts for combining similar cut and fill types into more manageable groups. Investigations (from shadowing planners at two major construction companies in the UK) have shown that it is common practice for project planners to group similar material types together in order to reduce the number of material categories used.

The method of splitting work into first and second stage cut and fill is common practice for earthmoving operations. The developed model accounts for this practice. Surcharging of

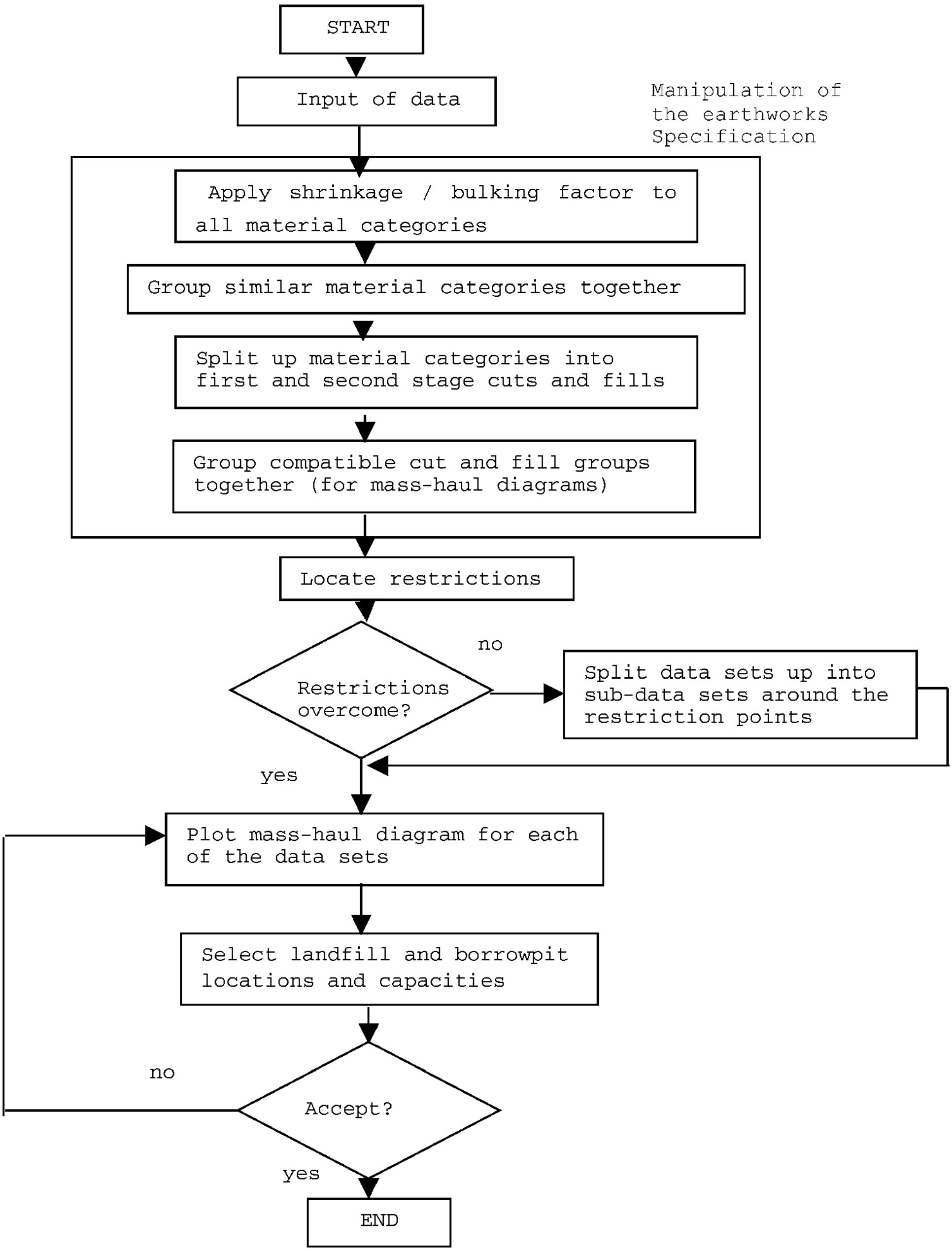

Figure 2. Flow chart of formalisation of data

embankments with subsequent removal of the surcharge after a specified period is assumed to be accounted for in the same manner.

The model also accounts for grouping compatible cuts with compatible fill types in order to define which types of cut can be used as fills for embankments. This practice is based upon knowledge about suitability of materials for fill.

The impact of overcoming a restriction (or not) is evaluated in the model by means of knowledge-based analysis. In order for such an evaluation to take place, activity sets that overcome restrictions together with activity sets that do not overcome the restrictions are needed. Both types of activity sets can be created.

Activity generation model

One of the difficulties in working with earthworks schedules or plans is recognising the relationships between cut and fill activities. Often, complex numbering systems are used to relate cut and fill activities. This approach, as well as being complex, can lead to work being either duplicated or omitted in the project plan.

A new approach has been developed that classifies an activity as a combination of cut and fill work. This can be used for all activities including landscaping and import and export type activities. This is because for any type of work that involves excavation or cut, there has to be a corresponding task of deposition or fill. Thus all activities have two parts associated with them, an origin (cut or import from a borrow pit) and a destination (fill or export to landfill). Temporary stores are simply classed as special areas of fill.

The use of cut-fill activity pairs has the advantage of reducing the number of activities. It also ensures that corresponding cut and fill sections of work are scheduled for the same time and that all work is planned for and not duplicated.

One of the drawbacks of using such an approach is the use of staged activities (where material may, for example, be temporarily stored). In such situations the staged activity has to be split into more than one activity. Figure 3 shows an overview of the activity generation model. The following sections discuss the various parts of this flow chart in detail.

Select mass haul

Each cut-fill grouping needs to be used to create a complete activity set. This part of the model ensures that each grouping is systematically selected and thus activities subsequently created for each material type.

Internal haul activities

Internal haul is an aspect of earthmoving that is commonly overlooked but should be included in an earthmoving project plan. Unlike main-line activities, internal haul activity boundaries (i.e., start and end chainages of the activity) correspond to the record boundaries of the Earthworks Specification. In the same manner as the main-line work, activities are created for each material grouping. Internal haul is generally carried out concurrently with the main-line movement of material.

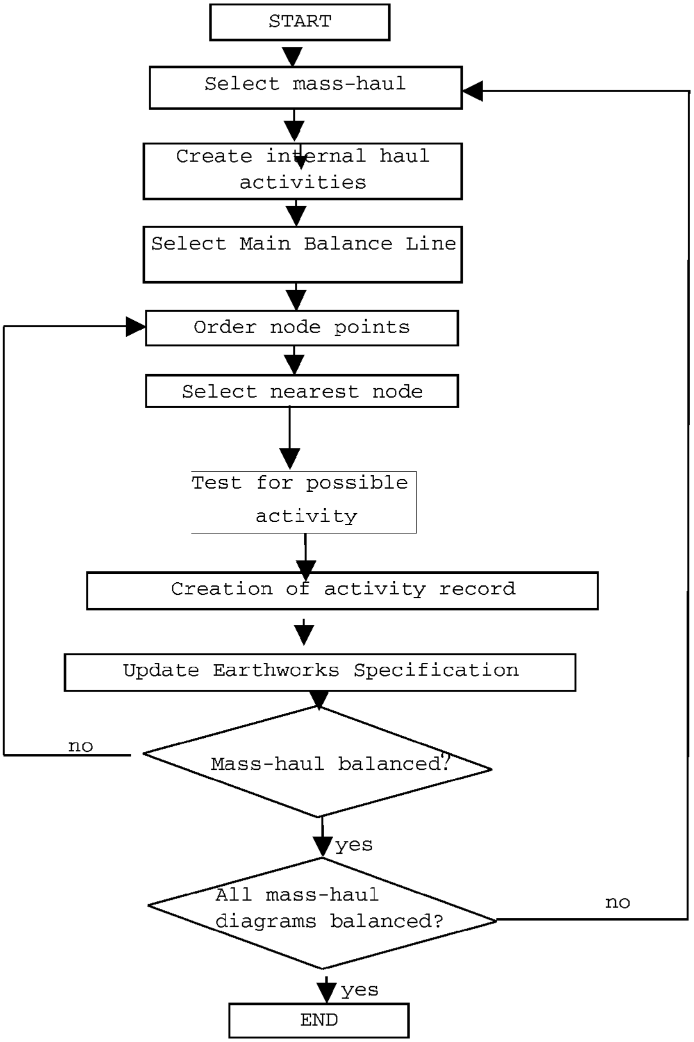

Figure 3. Activity generation

Algorithms have been developed to generate internal haul activities:

Start chainage of internal haul activity = Start chainage of earthworks specification record.
End chainage of internal haul activity = End chainage of earthworks specification record.
Volume of material moved = The smaller volume of the cut or fill category.

Select main balance line

The order in which balance lines are selected determines the pattern of activities created. A method has been developed for systematically varying the order in which activities are created, thus producing a means of creating varied activity sets.

An axis called the *Main Balance Line (MBL)* has been developed. This MBL is an axis around which activities are created. The order of selection of balance lines is indexed, based on nearness to the MBL. This defines the way in which the activities are generated. It is used for indexing the node points on the mass haul diagram, which are then used to determine the order in which the activities are created. The MBL must be within the volume limits of the mass haul diagram. However, the MBL does not have to lie on a node point (Figure 4).

Ordering the node points

Once the location of the MBL has been defined, the node points can be ordered or indexed. This process is carried out to provide a means of ordering the selection of balance lines for activity generation. The nodes are ordered with respect to nearness to the MBL (Figure 5).

The diagram shows a MBL together with a mass haul diagram. The numbers on the nodes indicate the order of closeness of nodes to the MBL and hence the order in which balance lines are selected.

Node points on the mass haul diagram are used as starting points for balance line positioning for a particular reason. When earthmoving is carried out, the operatives need to know where to finish an activity. It is common practice to complete either the excavation of a cut section or the fill of an embankment section. This practice is carried out (rather than reducing cut and fill sections to an arbitrary level) so that it is known where an activity should finish. An algorithm has been developed to implement this theory as shown in Figure 6.

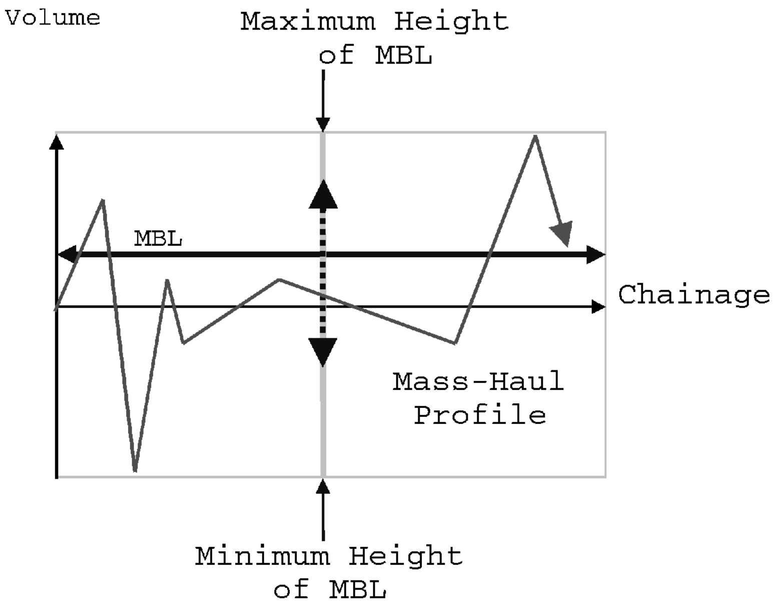

Figure 4. Position and range of the main balance line (MBL)

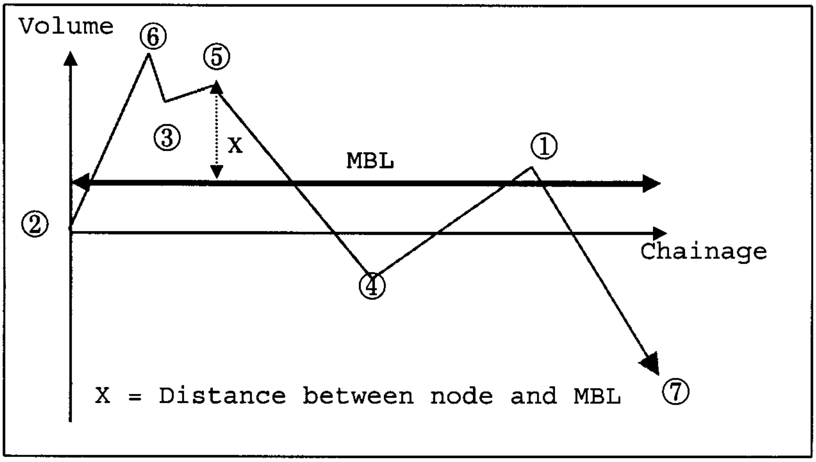

Figure 5. Ordering nodes with respect to the MBL

Select node

This process selects the node points in turn based upon the index of the nodes. This in effect selects the node points in order of nearness to the MBL. After an activity has been created, the nodes are re-indexed. Any node can be selected irrespective of the shape or profile that the adjacent nodes create with the node in question. This does not necessarily mean that an activity will be generated from the node in question (see the following section).

Test for possible activity

Upon selection of a node point, a test is needed to determine whether or not an activity can be generated. A test has been developed as follows: '*an activity can only be created if the balance line extrapolated from the node point in question intersects the mass haul profile a second time at a different location to the node point*'. This ensures the balancing of a cut and fill section.

As well as adjacent cut-to-fill sections, activities with clear'haul can be created. The model allows a varied number of node points along the clear'haul section. In a similar manner to the adjacent cut-to-fill activities, four different types of clear'haul activities can be created.

Creation of activity record

If a balance line successfully defines an activity (as shown in the above section), then an activity record is added to the activity database. This record contains information about the newly created activity. The following activity attributes are extracted from the balance line and the mass haul profile and included in the activity record. Such attributes are classed as '*Explicit Activity Attributes*' (EAAs):

- Cut start chainage
- Cut end chainage
- Fill start chainage

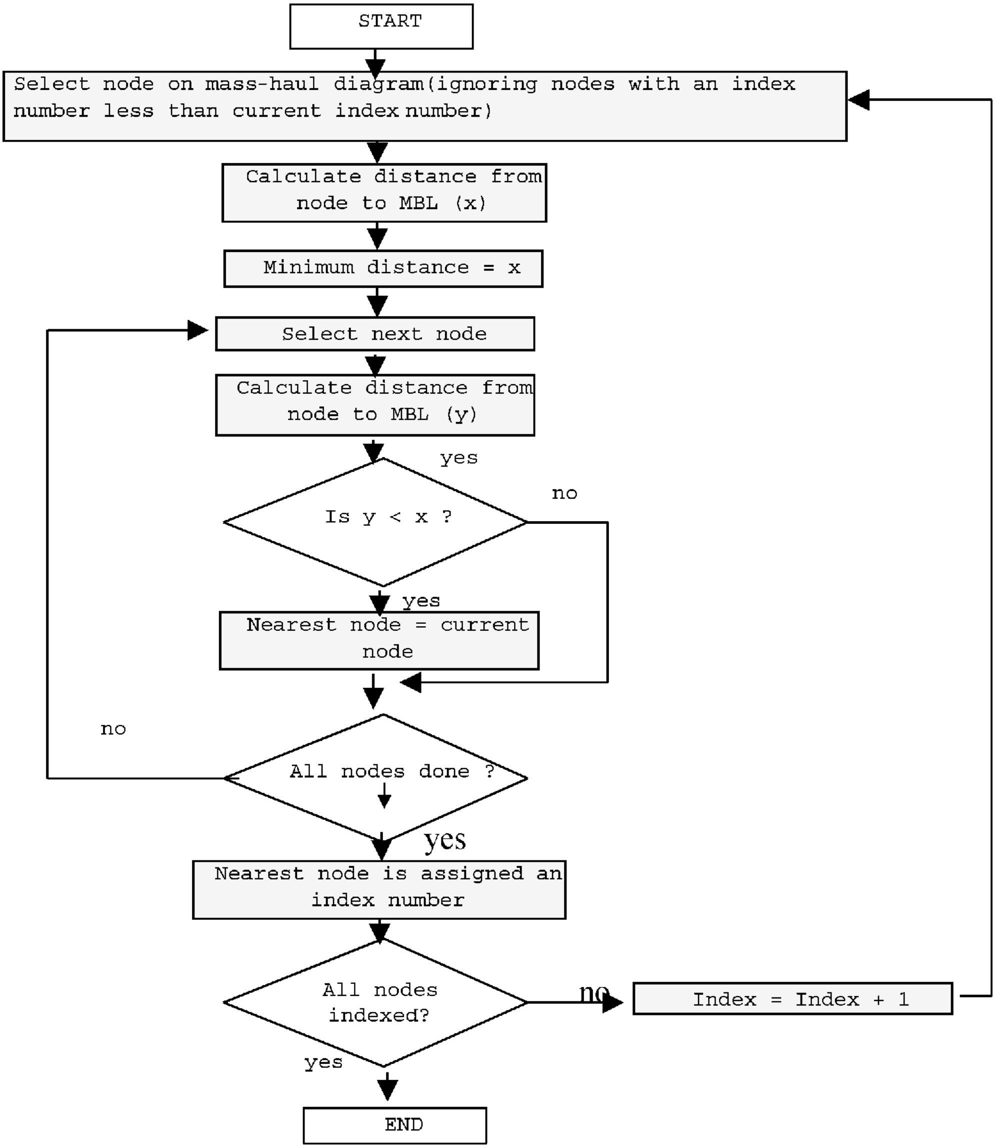

Figure 6. Algorithm for indexing node points

- Fill end chainage
- Volume of material being moved
- Type of material
- Type of activity (e.g., normal, import, or export).

These EAAs are used in the activity evaluation stage of the model.

Updating of the earthworks specification (and mass haul diagram)
Once an activity has been created, the earthworks specification (and corresponding mass haul diagram) need to be updated. An algorithm has been developed as shown in Figure 7 to account for this. Such a systematic mathematical approach ensures correct updating of the earthworks specification and hence correct subsequent activity generation. The algorithm as shown in Figure 7 is carried out each time an activity is generated.

Calculation of implicit activity attributes (IAAs)

As well as the explicit activity attributes, '*Implicit Activity Attributes*' (IAAs) are also created. IAAs are attributes that are calculated or produced using data from the EAAs or from other additional information concerning the activity or project (for example, haul distance).

The IAAs (together with the EAAs) are used in the knowledge-based analysis to draw conclusions (characteristics) about the activities. The EAAs and IAAs are calculated at activity (rather than project) level. These are then combined in the activity set evaluation.

Haul distance
Haul distance is defined as the distance between the centroids of a cut and fill section within an activity. The model assumes that the centroids of the cut and fill sections are exactly half

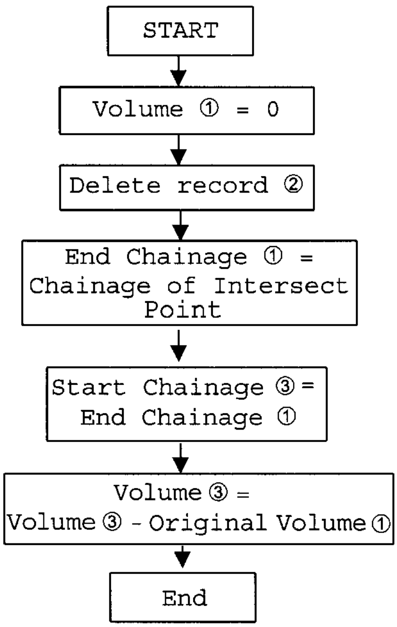

Figure 7. Updating earthworks specification sheet and mass haul diagram once an activity has been generated

way between the start and end chainages of both the cut and fill section of an activity. Such an assumption is based upon the fact that in the absence of any detailed information, the distribution of material within a section is symmetrical.

Haul distance is an important IAA as it is an indication of how far material has to be moved from its origin to its destination. It is an indication of how far the earthmoving plant has to travel but is not necessarily a true indicator of how much work has to be done to complete the activity. It is used to determine the type of plant to be used for an activity (see plant type section).

Clear'haul

Clear'haul is the distance between the end of a cut section and the start of a fill section within an activity. It is an indication of how much distance plant travels over areas that are neither cut or fill sections within the activity. Ideally clear'haul should have a value of zero, but this is not always the case.

Clear'haul factor

As stated above, used together, clear'haul and haul distance can be very useful attributes of an activity. Clear'haul factor is the percentage of haul distance that is clear'haul.

The clear'haul factor is used in the knowledge-based analysis to determine the amount of work that is useful in the activity. Ideally the clear'haul factor should have a value of zero (i.e., indicating an activity with no clear'haul). The higher the percentage, the less desirable the activity is as plant has to travel over a greater percentage of ground that is not part of the excavation or deposition of the activity.

Haul

Haul is the product of haul distance, the volume of material being moved and the associated material bulking factor. It is an indication of how much work has to be done to complete the activity. The bulking factor should not be confused with the similar shrinkage/bulking factor that is applied to areas of fill, which accounts for material being compressed during fill. Haul is used to determine the importance and scale of an activity.

Plant type

Plant type is determined by the distance associated with an activity. A test is carried out using the haul distance. If the haul distance is less than a pre-determined distance (1000 m is a commonly used distance), then scrapers are used; otherwise a gang of excavators and dump trucks are allocated to the activity. Plant type is used in the activity evaluation model as it provides further information about the reliability of the activity. It is also used to determine the cost of an activity.

The Subsequent Work Factor (SWF) is an indication of how tied the activity is to other earthworks activities. It uses the principle that activities with clear'haul cannot be started until any work within the chainages of the clear'haul has been completed. This ensures that haul is always over levelled terrain. This is an important factor as it determines how tied activities are to each other.

Figure 8 explains the SWF diagrammatically. An activity is defined as 'subsequent' if it crosses the 'critical chainage range' of the activity in question. From the diagram, it is evident that activities 1 and 2 are subsequent as they do cross the critical chainage range. However,

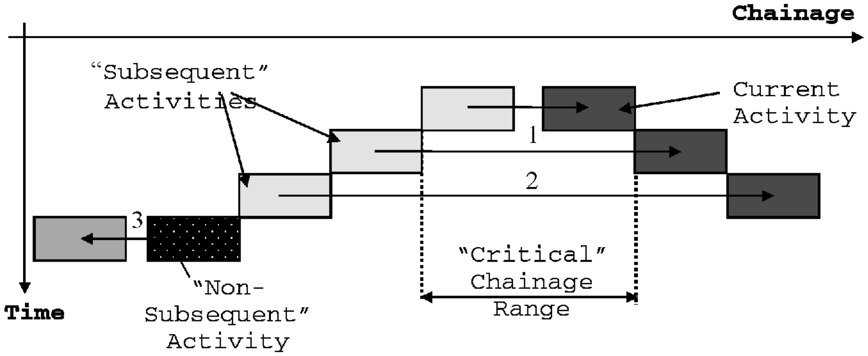

Figure 8. Subsequent work

activity 3 does not cross this range and thus is not subsequent. It should be noted that the SWF is not related to time.

The SWF is defined as:

$$SWF = \frac{\sum_{\text{for critical chainage activities}} (Haul\ distance * volume)}{\sum_{\text{for all activities}} (Haul\ distance * volume)} * 100\% \tag{1}$$

Duration

Duration of the activity is calculated based on the following parameters:

- Number of working hours in the day (hours)
- Rate of work of the excavation plant (excavator or scraper) (m^3/hour)
- Number of excavating plant
- Volume of material being excavated (m^3).

$$Duration = \left[\frac{Volume}{(Rate\ of\ work * No.\ of\ plant)} \right] * \frac{1}{Working\ hours\ in\ a\ day} \tag{2}$$

Bulking or shrinkage is not accounted for as the duration is based upon the work done by an excavator. At the time of excavation, the in-situ material is assumed to be at its original density and hence volume.

Volume/day

Volume/day is calculated by the division of the volume of material moved in the activity by the duration. This factor gives an indication of the efficiency of the activity.

Number of plant crossings

The number of plant crossings is calculated by examining the number of crossings along the extremes of the activity chainages. The number of plant crossings contributes to the complexity of an activity.

Number of trucks

When using fixed position excavators rather than scrapers to excavate material, a corresponding gang of dump trucks is needed to haul the material to the location of the fill. The number of trucks contributes to the cost of the activity. The number of trucks needed is determined by using the Match Factor formula (Caterpillar, 1987):

$$Match\ Factor = \frac{Number\ of\ haulers * Loader\ cycle\ time}{Number\ of\ loaders * Hauler\ cycle\ time} \tag{3}$$

Cost of activity

The cost of an activity is based upon the amount of resources required for the activity. This factor is used to determine the overall cost of the earthworks activity set and enables an economic comparison between the generated activity sets.

$$Cost\ of\ activity = \sum_{\text{for all plant types}} \begin{array}{l} Cost/hour * duration\ of\ activity\ \text{(Hours)} * \\ Number\ of\ units\ of\ plant \end{array} \tag{4}$$

Plant types include all excavation, haul, and compaction plant involved in the activity.

Creation of multiple activity sets

The aim of the activity generation model is to provide a means of creating different activity sets from a set of earthworks data. It is not to provide a means of creating an optimum activity set. This is not necessarily possible as there are many different (and often conflicting) parameters being considered that make optimisation difficult.

By creating different activity sets, the planner is provided with a selection of possible solutions to the planning problem. Evaluation of each set provides a means of indicating which set is the most suitable for the required purpose.

Different activity sets are created by using the standard activity generation model as discussed in previous sections but for different MBLs. By using different MBLs, different indexes (and hence activities) are produced.

Using different MBLs is the mechanism for creating different activity sets. Figure 9 shows an example of how the choice of MBLs affects the selection of activities.

As can be seen in Figure 9, by choosing different MBLs, different nodes and hence activities are created. The MBL approach allows a systematic selection of activity sets to be generated without any bias or preference given to any particular set.

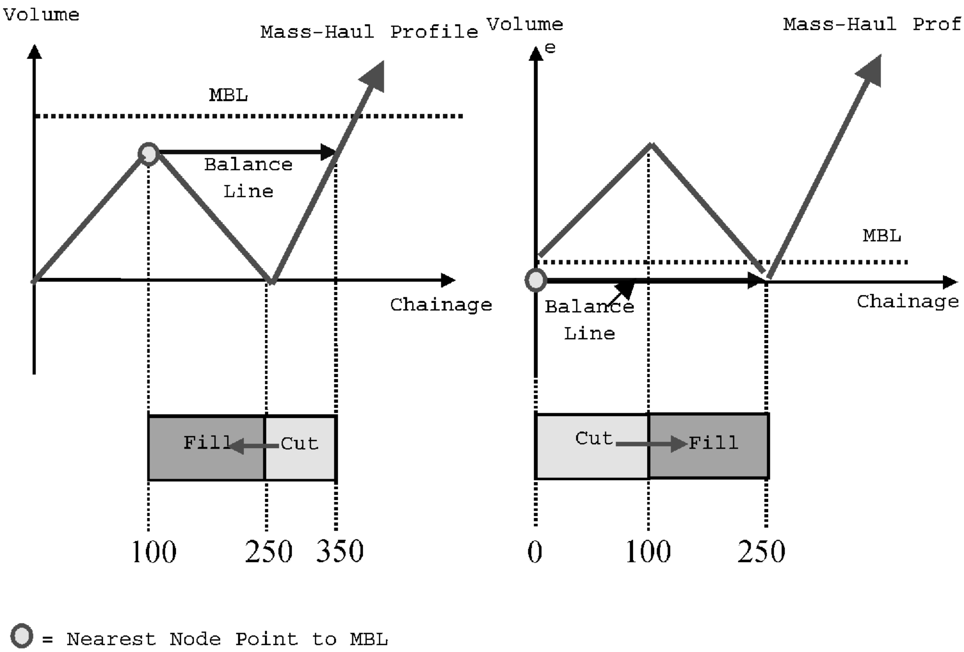

Figure 9. Effect of different MBLs on selection of activities

The following is an explanation of how the locations of the MBLs are defined.

$$Increment = \frac{(maximum\ volume - minimum\ volume)}{n}$$
$$Location\ of\ MBL = maximum\ volume - (i * increment) \tag{5}$$

where i is an integer between 0 and n, and n is the number of required MBLs (this is determined by the planner)

A suitable size of n needs to be determined. Too few increments may result in too few activity sets being created; likewise too many increments may result in repeated sets being created. The number of required MBLs is determined by the planner and is based upon the number of possible alternatives that need to be investigated. Interviews with planners have shown that in general no more than five activity sets would be compared and this figure should be used as a guide.

Computer system development and discussion

A software package based on the proposed model has been developed in order to be used to aid the production of earthworks activities. The package is able to generate activities automatically based on basic earthworks data that is input by the project planner.

The package enables a planner to enter earthworks data (volumes of material for cut and fill and the corresponding locations) in a spreadsheet type format. Any changes to the data can easily be entered and a mass haul diagram, which can be interactively updated, is produced. The data can be grouped together or split into different material types and the corresponding mass haul diagram plotted from this. Shrinkage and bulking of material, once it has been excavated, is also taken into account and the effects of the changes in these values can be seen interactively on the mass haul diagram. The results can be plotted graphically in the form of a mass haul diagram or sorted and re-presented in a tabular format.

Once the mass haul diagram has been created, the package generates balance lines for each of the material types and creates a set of activities to minimize the effective haul distance in the project. The relevant data (start and end chainage and haul distance) is then extracted from these balance lines and used in an earth plant cycle simulation model to generate earthworks activities.

The knowledge base system

Through experience gained in shadowing project planners together with research investigating possible routes to solving the earthworks problem, a suitable approach has been developed. The approach has been to use a comprehensive knowledge-based or expert system and link it with a plant cycle simulation model.

The expert system, based on a domain-specific knowledge base, is used to obtain information about the selection of activities. For it to be effective it should be able to infer the 'goodness' of a selected activity and give reasons why it has done so. The package is able to give reasons for decisions made and also gives the facility for the planner freely to accept or reject these decisions. The package has been written in Pascal and developed using Delphi environment.

The expert system enables the suitability of an activity to be found, together with reasons for such a decision being made. This is done by means of knowledge about earthworks and data specific to the project. The earthworks planning problem is complex in that there are no pre-defined activities. Thus, a tool is needed that can quantify the quality of an activity and give reasons for such a quality. It should also be able to produce explanations as to why an activity is *not* suitable for selection.

In this way the activity selection can both be monitored and, more importantly, improved. Planners can choose an activity; use the expert system to analyse the choice, view the analysis, and either accept or reject the computer's advice.

At present, it is typical for a subjective approach to be adopted when planning earthworks activities. With the introduction of this system, a more systematic approach can be developed with results that are based on reasoning more than instinct or personal preference being produced.

The knowledge base is the means by which knowledge is stored in the system. It has to be stored in a way such that it can be applied to data in order to produce useful advice together with explanations as to why certain decisions have been made.

Knowledge acquisition is the first step towards developing a knowledge base. This is a difficult process especially as planners are often not themselves aware of rules or reasons for their decisions. Past projects were studied in order to find patterns to earthworks planning. These examples were also discussed with project planners to enable building up a list of rules that are used when planning earthworks. This knowledge base is designed to be dynamic such that alterations or updates can be introduced at later dates. Below is a brief list of examples of earthmoving knowledge that have been included in the knowledge base:

- Minimum haul is preferred.
- Restrictions (such as rivers) have to be avoided or overcome.
- Starting points need to be near suitable access points.
- Laden uphill haul is avoided.
- If importing material, volume of material required for fill must be less than volume available from borrow pit.

Knowledge representation, once elicited, is also very important. Coding (external for the user and internal for the inference engine) is essential for an expert system. Codes that are instantly recognizable by the planner are used in the output of decisions together with reasons for such. A quantitative system has been developed to enable comparison of activities using a scoring system. Reasons for decisions are given in short English phrases such as ‘haul road not passable’ or ‘more efficient to export material to landfill site’, so that they are easily understood. This enables the planner to get an idea of the suitability of the activity as well as an explanation as to the level of its suitability.

The first stage in automation was to produce a system that allows planners to input an activity so that the software can evaluate it (based on knowledge and data provided). Thus, the planner will still manually select the activities but will have the help and support of the expert system to evaluate his or her decisions. The advice given by the package, if accepted, can then be stored in a temporary database and referred to (as additional data by the expert system) when a subsequent activity is selected.

The second stage was to enable the software to choose its own activities, thus fully automating the activity selection process. There are many applications for this, one of which is to implement it as a teaching tool. Planners could use the package to learn about and build up knowledge that is essential to earthworks planning.

The package not only can produce information about the suitability of activities, but can also produce a cost and duration result for each activity. This is achieved using a plant cycle simulation. The results obtained from the expert system are passed through to the simulation model.

The plant simulation model

Once the physical parameters of the activity have been defined (based on decisions made by the knowledge base system), a plant cycle simulation model, which is the subject of another paper, is used, which produces a cost and duration of the activity. It takes into account:

- Amount of work involved
- Type of work
- Availability of plant
- Distances hauled
- Weather conditions
- Rate of work of the plant.

Earthworks (that is, work that involves excavation, haul, and compaction) are generally carried out in two ways. The first and most common method is to use a gang of excavators and compactors with dump trucks feeding each. This method is more economical, especially when the haul distances involved are typically greater than 1 km. The second method is to use a scraper and compactor. This system uses a scraper to excavate and haul the material before it is off-loaded and compacted by suitable plant. This method is more suitable for haul distances that are less than 1 km.

The simulation model is connected with a resource pool. This pool consists of the total amount of plant that is available to the project. When an activity is to be carried out, plant availability is checked and, if the resources are available, then the activity can be carried out. Suitable distribution of plant to each activity throughout the project is important. Ideally time taken to carry out the earthworks should be kept to a minimum. This philosophy allows subsequent activities to commence at the earliest possible time, and also means that expensive earthmoving plant is hired for the shortest possible time (thus reducing expense).

The distribution of plant has an effect on the duration of each individual activity and thus some activities with special requirements may have preference over others. An example of this is an activity that is controlling the start time of a subsequent activity that is on the critical path of the project.

Conclusions

This paper has reviewed the developed model that generates multiple activity sets together with introducing the concept of activities having cut and fill components.

Ten types of activity can be created by the model including four cut-to-fill activities, four clear'haul activities, and two import/export activities. In addition to the activity generation facility, the model also produces 'explicit' and 'implicit' activity attributes that are utilised in the second part of the developed model—the activity set evaluation stage.

Traditionally, haul has been the predominant factor considered when planning earthworks. The need to allow planners to consider other factors has been recognised and implemented in the developed model.

From the development and testing of the model it can be concluded that:

1. The developed model provides a new means of planning earthworks activities.
2. The ability for multiple earthworks activity sets to be created is an effective decision aid for planners. As well as creating activity sets in a much shorter time, the ability to compare various sets allows the planner more scope when planning earthworks.
3. The use of cut-fill activity pairs is beneficial. As well as increasing clarity, they are useful in reducing errors (such as duplication of work or absence of origins or destinations of work). The graphical representation of these activities by using a modified time-chainage technique has simplified the interpretation of earthworks activities.
4. From testing on real projects, it has been shown that the model is able to generate activity sets that are comparable to those generated by a project planner.

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