Using agent-based simulation to manage logistics for earthmoving operations in construction

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Abstract

Planning earth moving projects involves numerous assumptions on the interactions between site vehicles, traffic and subcontractors which are described as agents in this paper. This paper discusses how agent-based simulations can be used to improve the planning of earthmoving activities in construction. This research is based on the London Gateway Port in which a significant portion of the project dealt with earthmoving operations.The observations based on this construction project indicated that dumper trucks were subjected to irregular travel routes and varying distances between the excavation and dumping areas. This was further compounded by related logistic activities affecting the progression of the earthmoving activity. Routing of material delivery affects both the cost and timing of the construction project. Efficiency gains based on reduction in working time can be optimised by planning a construction site from a logistics perspective. Estimating the delay of the earthmoving operation because of these interferences is difficult to measure and cannot be implemented at the planning process. Existing activity scanning tools typically eliminate surrounding logistic activities and therefore cannot be confidently relied upon during planning. Agents interacting with the earthmoving environment intend to underpin how the earthmoving operation might be planned to reduce spatial time clashes. The ability to use agent-based simulations to interact with the construction environment to predict efficiency and improve safety of the earthmoving operations is critical, as this cannot be implemented with existing activity scanning simulation tools.

Keywords: Earthmoving in construction, Agent-based simulation modelling, Dynamic spatial interferences, Site congestion, Site safety.

1. Introduction

It has been well documented that earthmoving operations in construction are very significant in terms of cost and productivity (Christian and Caldera, 1988; Navon et al. 2012). Earthmoving is characterised by the intensive utilization of machinery, therefore it is essential that sufficient planning is undertaken to optimise productivity of the relevant plant and machinery. At present there are no effective means of planning the earthmoving operations in the construction industry. As a result planners rely on their intuition and experience (Askew et al. 2002, Tawfik and Fernando, 2001) to determine activity duration

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and the optimum plant and equipment necessary for a particular operation. Surrounding site activities and clashes are often unaccounted for during the earthmoving operation planning process. Activity scanning tools can be applied in the field of mining; however they cannot be applied to earthmoving operations in construction specifically because of the nature of the operation. Clegg et al. (1997) highlight key characteristics of earthmoving operations in construction compared to mining:

- The quantity and type of material to be excavated can vary at different chainages;
- Excavation of material takes place over a series of chainages;
- The movement of dumper trucks are often affected by related construction logistic activities, causing bunching of trucks and irregular paths to their destination.

The motivation to discuss this research method was driven by a need to address these characteristics. The method described in this paper has been developed through a combination of the literature review regarding existing simulation tools and observations combined with qualitative data from the London Gateway Port Case Study which highlights the key areas for implementation of this proposed new tool. In this paper the methodology for a simulation tool using agent- based modelling for earth moving operations is presented. The applications are discussed in terms of how it can predict space time clashes within the surrounding site activities to promote productivity and site safety.

2. Case study: London Gateway Port Project

The observations for this case study were undertaken at the London Gateway Port Project between May to September 2011. Observations were undertaken using video footage of the operations onsite in the diaphragm excavation area as shown in figure 1. This data was subsequently studied to understand how the earthmoving operations are affected by the surrounding operations and logistics onsite. Construction of a diaphragm wall is a common repetitive process onsite which involves significant earthmoving operations and careful logistics coordination. This process is costly and often the inefficiencies cannot be predicted in planning using existing simulation tools. Figure 1 depicts a typical scenario taking place during the construction of a diaphragm wall, indicating other activities leading to inevitable spatial time clashes.

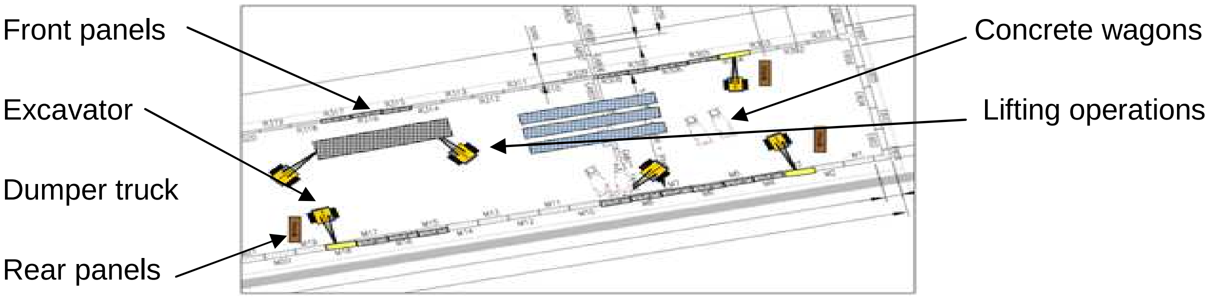

Figure 1: Typical plan view of a section of the construction site indicating other key activities

An earthmoving operation involved in diaphragm wall construction consists of three tasks: excavating material, hauling material and depositing fill material. The contractor used 2-3 articulated dumper trucks for the front wall and 3-4 articulated dumper trucks for the rear wall. In seldom cases one dumper truck driver will be allocated to interchange between different excavation panels. In this case study the dumper trucks were observed to gain qualitative and quantitative data regarding factors affecting efficiency onsite.

2.1 Excavation

The diaphragm walls (D-walls) are separated into six metre panels. The volume of earth which would be excavated from each panel varied slightly, therefore for the purposes of this study the volumes of the front and rear panels are taken to be $125m^3$ and $475m^3$ respectively. The time required to fill each bucket was a function of its capacity and the 'loadability' of the material being excavated as this varied with depth. At the start of each working day two dumper trucks are located near the excavator ready to be serviced. The average duration for excavating earth from 15 panels for the front D-wall was 12 minutes, and for the rear D-wall this average duration was 38 minutes.

2.2 Hauling Material

Once the trucks are filled they proceed along the haul route. Observations were made over three hours which indicated that there was a 75% probability that a truck would encounter spatial time clashes with other logistic activities which would delay its entry onto the haul curve. On reaching the discharge site the dumper truck queues briefly or deposits the material directly before returning to the excavation area. Upon arrival to the excavation area drivers were asked to park their trucks near the vicinity of the excavation area to minimise congestion in this area. These temporary 'holding areas' were often unmarked. As a result, they were often used by other subcontractors to execute their tasks. This caused unnecessary delays and confusion in terms of where the dumper truck should be held until it is called over to the excavation zone.

2.3 Summary of findings

The findings from the London Gateway Port identified the importance of incorporating the following in a planning tool:

(i) Defining waypoints for the articulated dumper truck to travel;

(ii) Spatial interferences affecting the productivity and movement of the earthmoving operation;

(iii) Average distance travelled by the truck from a loading area to the depositing area;

(iv) Interaction between different trades (subcontractors) leading to variation in productivity levels onsite;

(v) Spatial time clashes in alignment with safety onsite.

The site layout described in this paper is only a snapshot of site operations at a fixed time in space. It enables the authors to identify the aspects in which a simulation tool can be applied for planning of earthmoving operations.

3. Literature review of modelling scenarios on construction sites

3.1 Simulation Based Planning Tools

Simulation has previously been used in construction for process planning and resource allocation (Hammad and Zhang, 2011) because it is able to capture the dynamic behaviour of the processes being modelled (Marzouk and Moselhi, 2004). Many simulation tools have been developed, including CYCLONE (Halpin and Woodhead, 1976), MicroCYCLONE(Halpin 1977), RESQUE (Chang, 1986), COOPS (Liu, 1991), CIPROS (Odeh, 1992),STROBOSCOPE (Martinez, 1996) and, Simphony (Hajjar and AbouRizk, 1999). Of these tools, MicroCYCLONE (Halpin, 1973), STROBOSCOPE (Martinez, 1996) and Simphony (Hajjar and AbouRizk, 1999) are the most widely used systems in construction (Hammad and Zhang, 2011) because of their effectiveness and efficiency in simulating various construction projects. Zayed and Halpin (2001) applied simulation to concrete batching operations to investigate alternative solutions and resource management using MicroCYCLONE. Simphony was consequently used to model and analyse the tunnelling process using the Special Purpose Tunnel developed within the simulation tool (AbouRizk et al. 1999). Hassan and Grubber (2008) simulated concrete paving operations on the Interstate-74 using both EZStrobe and STROBOSCOPE. EZStrobe employs a simple graphical format based on activity cycle diagrams (Martinez, 2001). One of the advantages with this is the ability to model moderately complex systems without having to write advanced computer code, as it is required with the use of STROBOSCOPE (Hassan and Grubber, 2008).

3.2 Weaknesses of the current simulation based planning tools in construction

Whilst the simulation tools described in section 3.1 are able to provide information on the logistical relationships between the different resources, they are not well suited to define the spatial relationships between the different resources on the construction site (Hammad and Zhang, 2011). The main disadvantage with traditional scheduling techniques is their inability to define the spatial relationships between resources on the construction site (Dawood and Sikka, 2008; Dawood and Mallasi, 2006) which is regarded as a challenge in construction workspace management (Chavada et al. 2012). When modelling specific construction activities, these need to be carried out in a suitable simulation environment incorporating spatial time clashes onsite. Hammad and Zhang (2011) recommend that construction simulation models should be developed so that space can be represented explicitly to improve realism in simulation.

4. Spatial interferences affecting productivity

One of the benefits of simulating the construction environment and processes is that it is possible to ensure the reliability of the construction plan by checking it for potential collisions or other similar problems (Hammad and Zhang 2011) with obstacles on the site. Obstacles can be considered as *static* or *dynamic* (Hammad and Zhang, 2011). Static obstacles are primarily related to fixed objects and these are unable to move, as such information can be determined in advance. Simulation in construction predominantly deals with the static environment and therefore there is a need to also consider the dynamic aspects of the construction site (Hammad and Zhang, 2011). Dynamic objects are objects that move on site, such as mobile cranes, concrete wagons and other construction equipment. These obstacles need re-planning because of potential collisions (Hammad and Zhang, 2011). As such these obstacles influence the overall productivity of the earthmoving operation because of their route and hauling unit velocity. When modelling construction logistics during the planning stage it is important to include these obstacles as they influence the overall efficiency of the earthmoving system.

The above problems are also coupled with the workforce distribution density. As such, earthmoving projects in construction employ a fragmented workforce with a wide range of sub-contractors working on different areas of the site undertaking various tasks. For example construction of the diaphragm wall panel involves different subcontractors, such as excavators, banksmen, earthmoving operators, steel cage fixers, crane operators, concrete pour gangmen and concrete wagon drivers. These subcontractors work at different chainages and spatial time clashes are inevitable.

4.1 Methods for modelling spatial interferences in construction management

Researchers that have contributed towards this field have used multiple techniques to identify workspace congestion as it has been regarded as a major loss of productivity (Chavada et al. 2012). Zhang et al. (2007) used a cell-Discrete-Events systems Specification (DEVS) modelling approach to depict space resources in construction simulation. One of the advantages with this technique is that it enables conflict analysis, visualisation of the work site and availability of workspace which is critical in identifying bottlenecks to minimise delays (Guo, 2002). Ample research has been undertaken in relation to understanding spatial interferences in construction. Research undertaken by Sriprasert and Dawood (2003) proposed to use a multi-constraint planning algorithm which considered both time and space. Jang et al. (2007) used genetic algorithms to optimise space management with respect to material deliveries, staging areas and crane location. Mallasi (2009) developed a software prototype using genetic algorithm technique which optimised three decision variables: work execution direction, rate distribution types and quantity of work per week. Traditional methods of determining the optimal path in congested areas uses graphical techniques such as Djkstra’s Algorithm (1959), A*(Hart et al. 1972) and genetic algorithms (Holland, 1975). Hassoun and Sanghvi (1990) developed the parallel unconstrained Dijkstra optimal path approach to resolve the acute turns. Whilst these methods can be applied they pose certain constraints as they do not reflect the natural motion of the articulated dumper truck. It is essential that the method selected is able to generate a traversable path for a wheeled vehicle.

5. Methodology

5.1 Conceptual framework of agent- based model for planning site logistics

The key components of an agent- based simulation model for planning site logistics consists of the following (Walsh et al. 2007): (i) agents with diversity in agent types; (ii) work environment characteristics that relate to safety risks and are a function of location and space; (iii) plant and material equipment characteristics (iv) rules for interaction: agent to agent, agent to site, agent to plant and equipment; (v) agents adapting to certain properties and rules; (vi) changes in the work environment. The method proposed will have 3 key domains; agents in the construction environment, a path planning tool and a safe distance model for the agents.

5.2 Defining Agents in the construction environment

The methodology for this tool focuses on spatial time clashes between various agents onsite. These agents can be categorised into; static (concrete, diaphragm wall, muck away, site offices) and dynamic (heavy plant, vehicles, trajectory path). Subcontractors are not listed as agents within the scope of this methodology. Numerous interactions take place during the construction process which depends on the rules of participating agents. These typically include; agent to agent interaction (coordination), agent to site interaction (safety situations), agent to plant/ equipment (productivity). The agents will primarily continue executing the task until it is completed. The critical work environment characteristics that are relevant at this stage of the development include site layout, space availability, operating conditions and hazards. These factors arise as a result of site constraints, works scheduling and organisation practices which change continuously during the construction process (Haslam et al., 2005). The location of the work place and the availability of execution space affect both safety and productivity of the earthmoving operation.

5.3 Path planning using Bezier segments

5.3.1 Allocating a trajectory path

The technique of using interpolated B-splines is implemented (Arney, 2007) for generating a continuous trajectory using a series of waypoints to depict a static trail of the articulated dumper truck. This technique ensures accurate trajectory tracking coupled with efficiently avoiding unexpected obstacles. The main reasons for using B splines reflect the dynamic logistic movement of the articulated dumper trucks in construction, which are relevant in two ways: low order polynomials can be used to define a complex path comprising of tight turns and angles from the articulated dumper truck. Secondly changes in the construction environment are inevitable; therefore if any obstacles are present along the path of the route this needs to be reflected in the segment of the curve. The application of B-splines have gained ample attention in the field of dynamic path planning in construction logistics. Cubic curves are selected to represent a Bezier segment which is able to handle points of inflexions as shown in Figure 2. In order to construct a Bezier segment between each way point, internal control points must be selected.

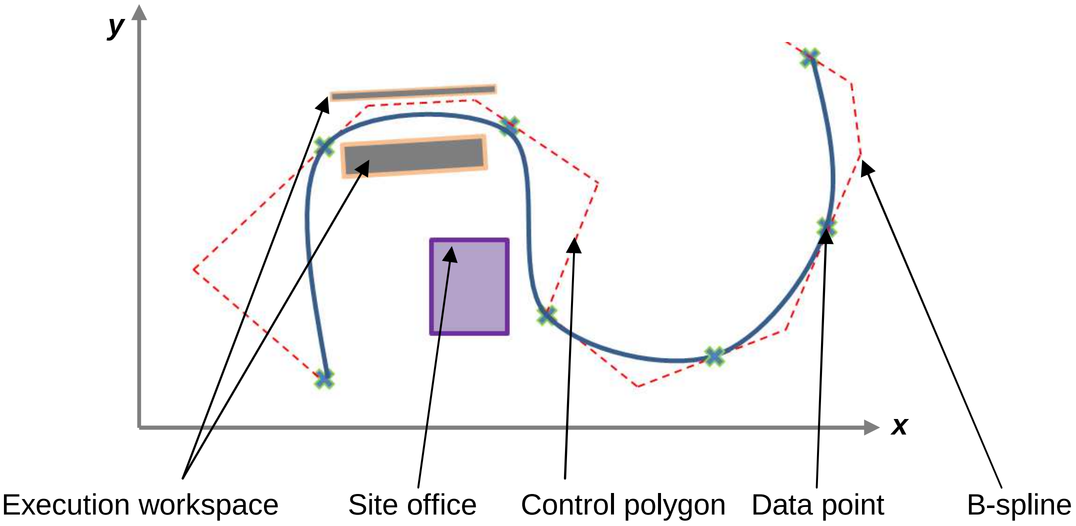

Fig 2: A cubic B-Spline precisely interpolating seven data points

Control points are defined by the tasks which need to be carried out by the agents. The user selects a series of points which will be denoted in Cartesian coordinates, whereby a cubic spline can be fit to this data set. Three vital properties can be said about this curve (Arney, 2007):

(i) The curve precisely interpolates the waypoints;

(ii) Curve lies entirely within polygon;

(iii) Continuous over entire parameter range.

The Bezier segment represents a smooth trajectory path by a dumper truck. This is beneficial as it can represent the path of a truck through different manoeuvres in congested areas which wouldn't be achieved using non smooth transitions. Another benefit of using this method is that it enables planners to identify the minimum distances which the dumper truck travels to other agents, leading planners to eliminate risk at its earliest stages. Further support to enhance decision making is made by the way the curve lies within the control polygon, which can reflect the curvature of the hauling route and positioning of road signs.

5.3.2 Avoiding obstacles onsite and defining safe travelling path

The nature of any construction site reflects the dynamic changes which takes place onsite. The initial path specification model provides a valid path based on a static environment. As such the initial described model would not incorporate dynamic activities such as other logistic activities and the construction personnel onsite. To incorporate dynamic obstacles, these are modelled as generating a force which is radially decreasing over a finite range and zero beyond it (Arney, 2007). The forces cause the path to be displaced if the object remains within close range of the line of trajectory. The magnitude of the force can be specified to create a displacement which reflects the geometry of the obstacle.

5.3.3 Interaction between the Bezier Curve and Agents

The agents described within this environment are software entities that respond to stimuli to act upon their environment (Russell and Norvig, 1995), and typically share the following four properties (Woolridge and Jennings, 1995): (a) autonomous behaviour, (b) ability to sense their environment, (c) ability to act upon their environment, and (d) rationality. The flow chart in figure 3 depicts how the articulated dumper trucks traversing along the Bezier segment curve interact with the site agents. In this example two distinct dynamic obstacles (agents) are presented which traverse omnidirectional. In the flow chart presented one agent is a 'two hundred tonne' crane with linear velocity of less than 15mph and another is a concrete wagon with linear velocity greater than 15mph. Both these agents bisect the hauling curve of the articulated dumper truck. Based on site observations static obstacles can also account for some losses in productivity. Therefore the control traffic lights, temporary storage or works area can be modelled. The agents are highlighted in pale orange on figure 3. Queuing developed on the haul route is caused by the articulated dumper trucks. On-going research to develop this model includes modelling different subcontractors such as agents and material storage areas to quantify space utilisation onsite.

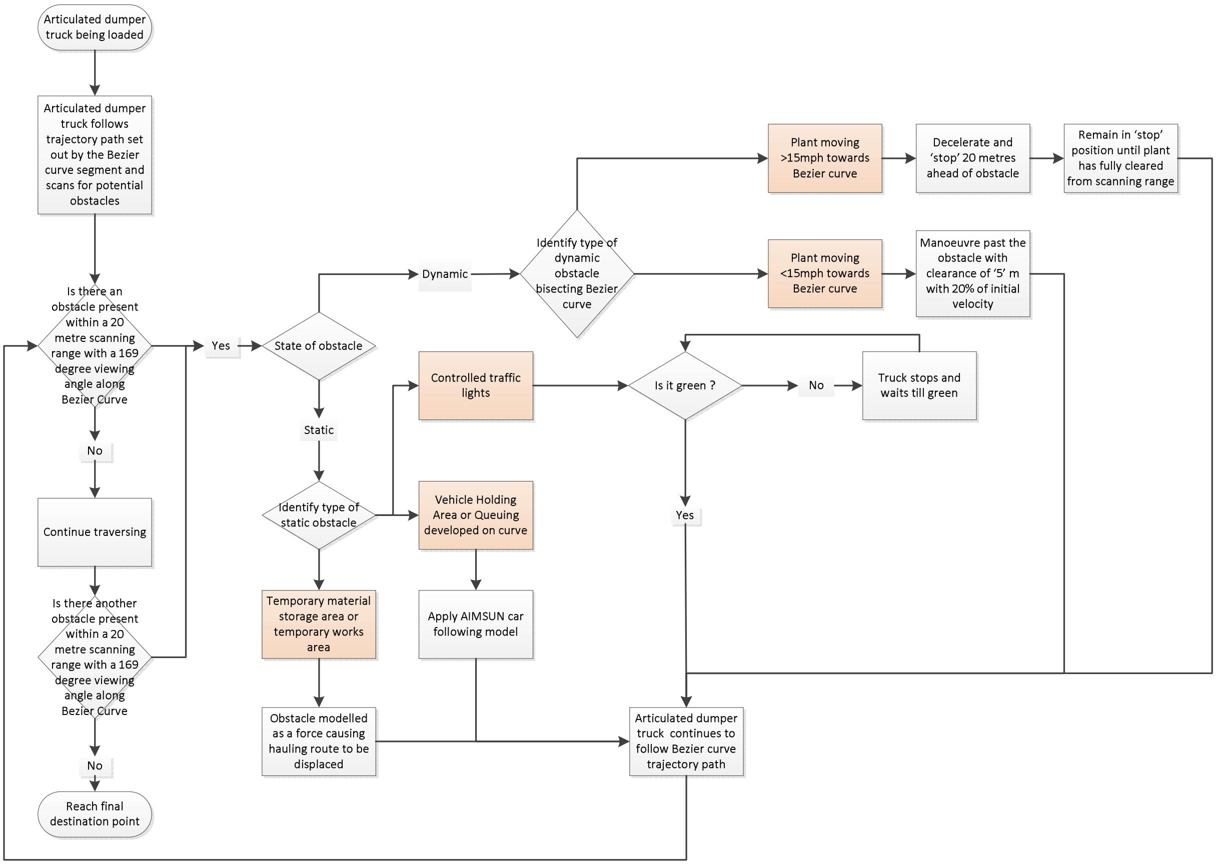

Fig 3: Flowchart to indicate the relationship of the Bezier Curve with the Agents

5.4 Avoiding dumper truck collision using AIMSUN car following model

The AIMSUN is a safety distance model, based on the model developed by Gipps (1981). Research conducted by Smith et al. (2010) emphasises the importance of estimating the variable plant speeds accurately which can be achieved using this model. The AIMSUN car following model reflects the scenario of the earthmoving construction site, as the dumper trucks will inevitably be temporarily stopped or slowed down to overcome unexpected obstacles, such as those described in the case study. Therefore a model which also incorporates a safe headway between the leading truck must also be considered. When a vehicle is constrained by the leading vehicle in front, the following vehicle tries to regulate its speed to maintain a reasonably safe headway with the leading vehicle to prevent a potential collision.

6. Discussion

When modelling construction logistics the environment which the agents behave in must be considered, so that a realistic estimate on productivity can be made on the earthmoving operation. Using agent-based simulation is a different approach to traditional approaches and takes into account the dynamic nature of the construction site. The interaction between the different agents' enables planners to change areas of the planning operation and adopt a logistics based perspective, through simulation. Furthermore this interaction will also enable planners to identify the reasons for delays and bottlenecks based on logistical delays onsite. It is expected that this method could enable planners to reroute the traversing paths. These measures could also lead to a safer site by identifying areas where hazards are more likely to take place.

Agent-based simulation can also be extended to analyse productivity on other logistic operations in depth. For example, in the case study productivity of the concrete batching plant was not fully optimised because there was no method to simulate the logistical operation for the concrete pour. It was identified through observations and discussion that concrete wagons which are required to fill the diaphragm wall after excavation are called upon based on the number of panels that require filling. Efficiency of this operation can be optimised using agent-based simulation in planning. This would ultimately reduce emission due to engine idling and queuing. Furthermore reduced number of trucks will reduce potential mishaps on a construction site.

In terms of emissions the proposed model does not take into account variations in terrain and ground altitude. Both these parameters can affect the distance travelled which also impacts levels of emission. Also in terms of safety the proposed model focuses on spatial time clashes with equipment and not personnel as this is a less predictable method. Validating how subcontractor agents behave can be difficult to prove, therefore the current methods which exist are limited. The 'interaction among root cause factors' (Walsh et al. 2007) framework is a potential method to address this issue.

Completion of the task in a timely and safely manner requires effective coordination of multiple agents (Walsh et al., 2007). Each agent has a set of properties based on personal factors and job responsibilities. The variables which need to be incorporated in the work environment include; knowledge, skill level or competency, experience (duration onsite) and average designated hours per week (Halsam et al., 2005; Hinze, 1997).

7. Conclusion

This research has endeavoured to highlight how earthmoving operations in construction logistics can be planned and better managed using agent based simulation modelling. The case study intended to show how earthmoving operations were affected by other activities in the same working environment. Using agent-based simulation during planning in earthmoving operations involves modelling complex multiple repetitive interactions (Walsh, 2007).

This research has highlighted the relevance of simulating the dynamic nature of the construction site using a vehicle model to help planners identify and eliminate potential spatial time clashes onsite. The authors believe that this approach will optimise productivity by increasing the efficiency and safety of earthmoving operations.

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