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Agent-based modeling and simulation of earthmoving operations

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ABSTRACT

Discrete-Event Simulation (DES) models are constructed from sequential duration-based activities. DES is used in modeling several construction operations including earthmoving. Current earthmoving models cannot accommodate equipment units with different specifications performing the same task. In addition, activity durations are calculated based on primitive methods such as interpolating existing durations of similar activities in previous projects. Finally, model elements behave in a predetermined manner, ignoring special operational real-life scenarios that occur due to resource constraints. These limitations often lead to inaccuracies in calculating productivity and equipment utilization. This paper applies Agent-Based Modeling and Simulation (ABMS) as an effective bottom-up tool to modeling earthmoving operations. An Agent-Based (AB) earthmoving model consisting of smart, adaptive agents is developed. Each agent is assigned a state chart and a set of static and dynamic properties (attributes and variables) to direct its interactions with the environment and with other agents. This framework proves how modeling earthmoving from the agent's prospective and basing agents' interactions on their properties allow for modeling equipment units with different specifications performing the same task (e.g. trucks of different capacities), as well as for an accurate representation of activity durations, resource handling and resource constraint scenarios. A Java-based application named Agent-Based Simulator for Earthmoving Operations (ABSEMO) is developed as an implementation of the proposed model. ABSEMO will be helpful to contractors in planning earthmoving operations according to the AB approach. A real-life case study of a riverbed excavation in a dam construction project is simulated using ABSEMO, and the results are compared with those obtained from existing simulation models to verify ABSEMO's logic. A percentage difference of 0.42% from the existing results is obtained, indicating that the model's flow of resources is indeed accurate.

1. Introduction

One of the most common applications of simulation in the construction industry is the simulation of earthmoving operations. Since these operations are typically lengthy in duration and fall on the critical path of construction projects, accurate planning is crucial in ensuring project success. And unlike other stages of the construction project, where manpower is the most relied-on resource, earthmoving operations are considered equipment-intensive, utilizing large and expensive fleets of trucks, loaders, bulldozers, etc. Thus, improving the efficiency of earthmoving operations is a primary objective from the contractor's point of view [20]. The cyclic nature of earthmoving operations and the type of work tasks they involve make the simulation process a valid planning tool for forecasting productivity and costs of these operations [31].

The nature of Discrete-Event Simulation (DES) provides, in most cases, a sufficient solution to modeling most construction operations, especially on the technical level. Furthermore, to address the decision-making aspect of construction management, recent efforts suggested the utilization of System Dynamics (SD) to account for the complex strategic level when simulating construction operations [3]. The main objective of this paper is the introduction of Agent-Based Modeling and Simulation (ABMS) into earthmoving operations for the purpose of enhancing current practices and overcoming limitations of current research work. These limitations include primitive methods for calculating activity durations, the inability to accommodate equipment units with different specifications performing the same task and ignoring unique scenarios of resource constraints. This major objective can be broken down into the following sub-objectives:

- Develop a detailed agent-based (AB) model of earthmoving operations, which captures the properties and interactions of model elements.
- Design a stand-alone ABMS software system for earthmoving operations and verify the model using a real-world case study.

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2. Background

ABMS is based on the idea of simulating the interactions of smart and autonomous objects, in order to identify, explain, generate and design emergent behaviors (Chan et al. 2010). Agents are self-contained entities that have the ability to control their own actions based on their perception of other agents and their surrounding environments [11]. Unlike DES and SD, which are considered as top-down modeling techniques, ABMS is a bottom-up modeling approach, in which model elements are built before the process is examined as a whole. Plus, ABMS has no specific convention on time progression during the model run; it can be discrete, continuous, or a hybrid of both (Chan et al. 2010). ABMS has the potential to have extensive effects on the way researchers use laboratories to support their research, and businesses use computers to support decision-making [21]. In ABMS, there is no need to make excessive assumptions or to direct the model in a way which is acceptable by the capabilities of the simulation technique.

2.1. *ABMS applications in civil engineering and construction management*

The majority of ABMS applications in civil engineering and construction management are focused on the following areas: 1) supply chain management [19,29]; 2) construction claims management [9,26]; 3) infrastructure management [23,27]. Supply chain management involves highly complex chains of interacting entities. Sharing information about stocks, costs, quantities and schedules is vital to assuring successful supply chain operations. Likewise, construction claims management involves interaction among project participants such as contractors and consultants. It involves discussions, sharing of information and organizing work tasks. Infrastructure management using ABMS is a promising topic, in which components of an infrastructure system are treated as interacting agents. Governments, infrastructure management agencies, infrastructural assets and users are all modeled as intelligent agents with attributes and goals. This can help anticipate performance, plan maintenance and manage budgets. There are a few other ABMS applications in other construction management areas including construction equipment management [30,35], bidding strategies [5], procurement [8], construction site safety [12,18,24] and construction workers' behavior [1,28].

2.2. *The need of ABMS in earthmoving planning*

There is a need to incorporate AB technologies with significant construction operations such as earthmoving. This must be completed in a smart and flexible paradigm that accepts various types of data, maintains a presentable view of model operation and analysis, produces accurate results, and most importantly, overcomes the limitations of currently used techniques. This research aims at rebuilding the methodology of creating earthmoving simulation models, based on the AB approach. While the application of simulation in earthmoving remains a well-researched area ([13,16,22,31], Smith et al. 2000), the vast majority of work is based solely on a DES or on a DES-SD hybrid system [3]. The following points discuss the major limitations of earthmoving modeling and simulation and indicate how ABMS would address these limitations:

1. Basic methods for calculating activity durations: Earthmoving activity durations used in simulation models are obtained from historical data calculated mainly by field observations. These durations are basically abstract numbers obtained for specific types of equipment units working together. For example, based on data from a previous project, a contractor using DES to plan an earthmoving operation can design the truck loading activity to last 3 min. But if the capacities or conditions of the equipment units to be used in the project have changed, this number is scaled up or down based on the planner's experience. An AB model would better address this issue, since it would administer interaction scenarios from the agent's (equipment unit) prospective. Each unit would have a set of properties that directs its interactions with other agents, making it easier to account for different combination of equipment units working together. Instead of assigning a certain duration for the interaction between units X and Y and assuming both are passive objects in the operation, both units would be assigned a set of properties. The output (duration, quantity moved, etc.) of the interaction between units X and Y relies on the properties of both agents in a way that if a new agent is introduced to interact with unit X or Y, no added assumptions to the model is necessary to force a new output; the new interaction will automatically produce appropriate output. This issue is further addressed in the AB model development section, when discussing the properties, state charts and interactions of agents in the proposed model.
2. Inability of accommodating equipment units with different specifications performing the same task: Since it is not possible to assign more than one duration for a certain activity in a DES model, planning an earthmoving operation with trucks of different capacities becomes a major challenge. Assigning larger loading durations for larger trucks is not possible in DES models, unless each truck type has its own path and queues in the model. However, this cannot be done in most cases, especially if one server is working with multiple units and therefore needs to process them in different durations. A simplifying assumption that is often used in such cases is to treat all units as if they are of the same type by assigning their service duration a weighted average of the service duration of all units. Since an AB model is based on individual agents performing certain tasks, every agent can have different properties, and accordingly different outputs when interacting with other agents or with the environment. For example, three trucks with three different capacities can all be modeled by an AB model, and every truck can have a different loading duration. These trucks would also queue up together, be served by a single or multiple loaders, etc.
3. Ignoring unique scenarios of resource constraints: Model elements in DES behave in a predetermined manner, ignoring special operational real-life scenarios that occur due to resource constraints. In DES earthmoving models, the quantity of earth to be excavated is usually added to the model in the form of truckloads. So, a 100 m^3 of earth is equal to 20 truckloads when trucks of 5 m^3 capacities are used. But if 7 m^3 trucks are used instead, after 14 trucks get loaded, 2 m^3 is left out. In practice, this 2 m^3 is assumed to be a truckload. An AB model would address this issue through its representation of agents' properties. Equipment units in an AB model possess both static and dynamic properties, referred to as attributes and variables respectively. Attributes are used in regular interaction scenarios, while variables are flexible and can be used in special interaction scenarios. Whenever two agents are engaged in an atypical procedure, they can accommodate the change using their variables. In the previous example, both the loader and the truck agents can be assigned a *capacity* attribute and a *carried earth* variable. During the process of loading 14 trucks with 5 m^3, both the loader and the trucks utilize their *capacity* attribute. However, the 15th load requires the loader to carry 2 m^3 only, setting its *carried earth* variable to 2 m^3. Consequently, the loader fills the truck with that quantity, increasing its *carried earth* variable by 2 m^3. Similar scenarios are investigated when building agents' state charts in the AB model development section.

Marzouk and Moselhi [17] developed an object-oriented simulation model for contractors to plan earthmoving operations with uncertainties. Their system utilized DES but with equipment units being modeled and treated as individual objects. Although their work was the first to account for equipment units as individual entities with properties (e.g. ID and capacity), there model was still based on DES, and no solution to address the aforementioned limitations could be introduced.