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Formulation and analysis of dynamic supply chain of backfill in construction waste management using agent-based modeling

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ABSTRACT

Backfill is the excavated material from earthworks, which constitutes over 50% of the construction wastes in Hong Kong. This paper considers a supply chain that consists of construction sites, landfills and commercial sources in which operators seek cooperation to maximize backfill reuse and improve waste recovery efficiency. Unlike the ordinary material supply chain in manufacturing industries, the supply chain for backfill involves many dynamic processes, which increases the complexity of analyzing and solving the logistic issue. Therefore, this study attempts to identify an appropriate methodology to analyze the dynamic supply chain, for facilitating the backfill reuse. A centralized optimization model and a distributed agent-based model are proposed and implemented in comparing their performances. The centralized optimization model can obtain a global optimum but requires sharing of complete information from all supply chain entities, resulting in barriers for implementation. In addition, whenever the backfill supply chain changes, the centralized optimization model needs to reconfigure the network structure and recompute the optimum. The distributed agent-based model focuses on task distribution and cooperation between business entities in the backfill supply chain. In the agent-based model, decision making and communication between construction sites, landfills, and commercial sources are emulated by a number of autonomous agents. They perform together through a negotiation algorithm for optimizing the supply chain configuration that reduces the backfill shipment cost. A comparative study indicates that the agent-based model is more capable of studying the dynamic backfill supply chain due to its decentralization of optimization and fast reaction to unexpected disturbances.

1. Introduction

During the construction of underground structures, backfill materials (e.g., sand, gravel, rock, and clay) are firstly excavated and then stockpiled on-site for backfilling when the construction is completed (Fig. 1) [1]. Generally, due to the high holding cost, limited site area or rain water degradation of the soil, some of the stockpiled backfill becomes surplus or undesirable and will be exported to landfills or other construction sites that execute backfilling. When the construction is completed, the stockpiled backfill is used for filling the excavation. If the stockpiled backfill is less than the total demand, the extra amount can be imported either from commercial sources or from other construction sites that execute excavation. Normally, importing or exporting the backfill between construction sites is more economical than landfills or commercial sources. Moreover, it is estimated that the backfill exported to landfills constitutes over 50% of the total construction wastes [2,3]. For these reasons, improving the recovery efficiency of backfill between different construction sites is a cost-effective and environmentally–friendly practice, and should be encouraged.

However, there are several challenges in the reuse and recycling of backfill. The first challenge is that construction sites are often operated by different firms that make decisions independently. Sometimes, due to the lack of appropriate information sharing and coordination between the firms, reuse of backfill among the construction sites may not be cost-effective and efficient. Secondly, the supply chain network for backfill shipment changes dynamically, which increases the complexity in solving the logistic issues. As shown in Fig. 2, the backfill supply chain is a network comprised of a landfill, a commercial source and construction sites, some of which carry out excavation and potentially export backfill (denotes by P, i.e., backfill producer), some of which refill excavated areas and potentially import backfill (denoted by C, i.e., backfill consumer). The network structure of a backfill supply chain can change randomly whenever a new site is established, an existing site leaves, or a site alters its state from excavation to backfilling

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(as shown in Fig. 2b). The inefficient coordination as well as the "dynamic nature" of a backfill supply chain result in a number of barriers for the reuse of backfill. In order to overcome these difficulties, a holistic approach is needed to model and analyze the coordination in the dynamic supply chain of backfill.

The application of supply chain management (SCM) in construction has been widely studied in the past few years [4,5]. In fact, there is a trend to adopt SCM techniques to deal with the environmental impacts of various construction activities. Cheng et al. [6] presented a service oriented framework based on the Supply Chain Operations Reference (SCOR) model for performance monitoring of construction supply chains. The SCM framework was later extended to quantify and monitor the environmental footprint generated by the participating members in a construction supply chain [7]. Ofori [8] presented the use of SCM to integrate the construction processes in Singapore for enhancing their environmental performance (e.g., reducing waste, and recycling material). A survey study presented the adoption of supply chain partnership (e.g., among contractors and suppliers/recycling companies) for an effective control and minimization of construction wastes [9]. By far, the previous studies have addressed some environmental issues (including waste) by integrating construction supply chain participants, but their models and methodologies only applied to supply chains with regular and specific cooperation relationships between the participants. No literature has focused on dynamic supply chains with participating members that can change their operational states and cooperation relationships. Hence, there are needs to investigate and identify an appropriate approach to model the dynamic supply chains.

Generally, there are two modeling paradigms, i.e., centralized and distributed, to analyze a supply chain issue. The centralized approach is any process where decision making is made by a central authority. The established method for the centralized approach is mathematical programming and its application in SCM has been investigated in a number of studies [10–12]. Tsiakis et al. [13] used a mixed-integer linear programming approach to design a multi-product and multi-echelon supply chain, considering the demand variance. Nagurney et al. [14] developed an integrated supply chain network model which allowed determination of the optimal network flow of products that reduced the transportation cost.

Differing with the centralized modeling paradigm, decision making in a distributed approach is often implemented by a large group of individuals geographically distributed in a region [15]. Agent-based modeling (ABM) is considered the most typical distributed approach for analyzing the supply chain performance. Since the concept of ABM was proposed, it was defined as an emerging technology where a number of intelligent agents interact with others and/or their undying environment in order to reach the designed objectives given by the model developer [16,17]. In general, an ABM model consists of three components: (1) agents, with static and dynamic attributes and decision making rules; (2) a set of agent relations and the methods of interaction; and (3) an environment where agents are settled [18]. Agents are the key elements of an ABM model and they are expected to exhibit the following characteristics [19]:

- Autonomous: agents should operate without the control and direct intervention of human;
- Social: agents should be able to interact with other agents and their underlying environment via a communication protocol or algorithm;
- Reactive: agents should be responsive (in a timely fashion) to the changes in their underlying environment;
- Goal-directed: agents should be capable of flexible actions and have some goal to achieve.

Model developers need to identify and program the characteristics to build an ABM model. By simulating the agent behaviors and interactions in an underlying environment, the effects of these agents on the whole system can be observed. The beauty of ABM, over other modeling approaches, lies in its connections to many other fields including complex science, system dynamic, computer science, management science, and many other transitional modeling and simulation theories [20]. Although the systems to be studied become more complex and beyond the capacity of many traditional modeling approaches, the theoretical foundations and the distributed nature of ABM still make it capable of analyzing and solving problems of a complex nature. Studies on the use of ABM in SCM have been investigated in the past few years [21–23]. Shen et al. [24] provides an update review on the application of ABM in the manufacturing industry including supply chain enterprise collaboration. Julka et al. [25] developed an ABM model for analyzing the effects of business policies on the chemical supply chain participants. Akanle and Zhang [26] proposed an agent-based framework for optimizing the configuration of a supply chain to deal with uncertain customer demand. In these ABM studies, the participating members in a supply chain were often emulated by agents. Model developers extracted useful information to formulate relevant policies based on the agent behaviors and performances in a designed scenario.

In this study, we attempt to identify an appropriate modeling paradigm to analyze the dynamic supply chain for improving the waste recovery efficiency of backfill among various construction sites. Both the centralized approach and the distributed approach

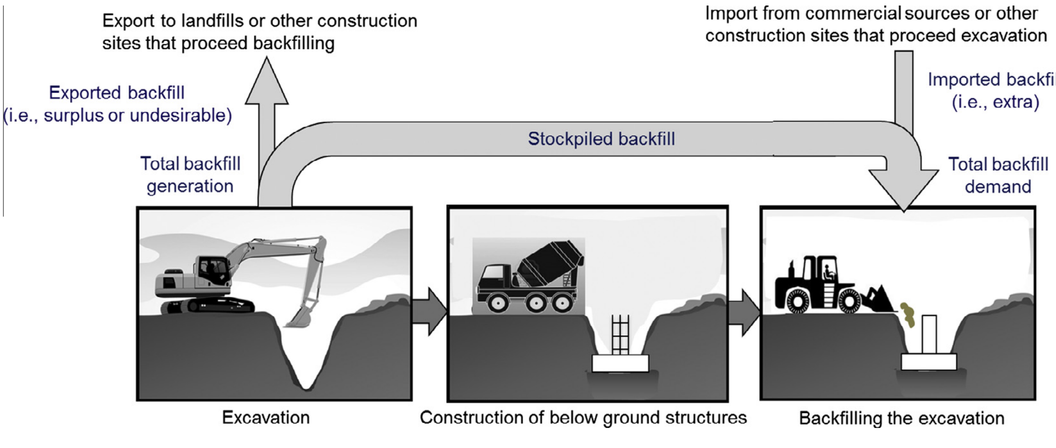

Fig. 1. State of a construction site in terms of backfill generation and consumption.