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An evolutionary multi-objective optimization system for earthworks

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ABSTRACT

Earthworks involve the leveling or shaping of a target area through the moving or processing of the ground surface. Most construction projects require earthworks, which are heavily dependent on mechanical equipment (e.g., excavators, trucks and compactors). Often, earthworks are the most costly and time-consuming component of infrastructure constructions (e.g., road, railway and airports) and current pressure for higher productivity and safety highlights the need to optimize earthworks, which is a non-trivial task. Most previous attempts at tackling this problem focus on single-objective optimization of partial processes or aspects of earthworks, overlooking the advantages of a multi-objective and global optimization. This work describes a novel optimization system based on an evolutionary multi-objective approach, capable of globally optimizing several objectives simultaneously and dynamically. The proposed system views an earthwork construction as a production line, where the goal is to optimize resources under two crucial criteria (costs and duration) and focus the evolutionary search (non-dominated sorting genetic algorithm-II) on compaction allocation, using linear programming to distribute the remaining equipment (e.g., excavators). Several experiments were held using real-world data from a Portuguese construction site, showing that the proposed system is quite competitive when compared with current manual earthwork equipment allocation.

1. Introduction

In Civil Engineering, a great majority of construction projects require earthworks activities prior to the construction of any structural element. Earthworks are engineering processes by which the ground surface in a target area is leveled or shaped through the moving or processing of the geomaterials that comprise it. It usually involves the excavation of these geomaterials, which can then be loaded and hauled to new areas to be spread and compacted into embankments, and may also include intermediate steps, such as material treatment or layer wetting. Nowadays, technical and environmental concerns require that, whenever possible, embankment fronts be built using mostly the material excavated from the construction site itself, in order to take maximum advantage of available materials and avoid the use of other materials brought in from outside borrowing areas. Earthwork tasks are reliant on heavy mechanical equipment, namely excavators (material excavation and loading to transportation equipment), dumper trucks (transportation between excavation and embankment fronts), bulldozers (material spreading so as to allow for compaction) and compactors (Hola & Schabowicz, 2010; Zhang, 2008). This is one of the main reasons that make earthworks to often incur the highest percentage costs and durations in road and railway construction projects, implying an increased importance regarding their automated optimization (Miao, Sun, & Li, 2011).

Under this context, it is essential to optimize all available earthwork resources under two key objectives: cost and duration. Both depend on the availability of equipment and also on equipment allocation throughout the project. This is a nontrivial task due to several reasons. There is a vast number of possible equipment allocation combinations, thus the search space is large. And while there is often high competitiveness, where the pressure is to provide the least possible costs and durations (Moselhi & Alshibani, 2007), contractors and project designers often settle for an allocation solution that is mostly based on their own intuition and experience. Moreover, trade-offs need to be set between cost and duration, since these objectives can also conflict. For instance, a less expensive solution may use less amount of equipment, which in turn will result in higher project durations. Contrariwise, allocating more equipment will increase project costs, but decrease durations. However, a prolonged use of equipment implies higher

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fuel consumption and maintenance expenses. Furthermore, as an earthwork construction progresses, the equipment must be optimally reallocated in order to advance through successive construction phases, characterizing this as a dynamic multi-objective optimization problem.

Ideally, earthworks should be optimized automatically. Considering the nontrivial characteristics of earthworks optimization (e.g., large search space and conflicting goals), pure conventional Operational Research (e.g., linear programming) and blind search methods are infeasible. An interesting solution is to adopt metaheuristics, which are flexible optimization methods capable of searching interesting search space regions under a reasonable use of computational resources. Several studies have adopted metaheuristics to earthwork optimization, such as genetic algorithms (Marzouk & Moselhi, 2002; Moselhi & Alshibani, 2007; Xu, Wang, & Xia, 2011) and swarm intelligence (Kataria, Samdani, & Singh, 2005; Miao et al., 2011; Nassar & Hosny, 2012; Zhang, 2008). However, many of these studies focus on single tasks or partial processes that comprise earthworks, such as excavation and hauling (Edwards & Griffiths, 2000; Kataria et al., 2005; Nassar & Hosny, 2012; Xu et al., 2011), in an attempt to deal with the high complexity of the problem. Therefore, these systems lack the advantages of a global optimization of execution durations and costs throughout all construction phases. In terms of optimization objectives, existent systems tend to be limited to single objective optimization, such as cost (Marzouk & Moselhi, 2002) or duration (Kataria et al., 2005), or attempt to consider both objectives via a weight-based optimization (Zhang, 2008). Although these solutions are considered effective in reducing computation effort requirements, they overlook the advantages of optimizing both objectives simultaneously. Even if it can be looked at as multi-criteria optimization, the weighted-based approach used in (Zhang, 2008) only outputs a single trade-off for a particular weight combination (e.g., 0.8 for first criteria and 0.2 for second). Yet, often there is not a single optimal trade-off solution, but rather a set of trade-offs with conflicting objectives. Thus, a much natural multi-criteria optimization approach is to optimize a Pareto front of solutions, where each solution is called non-dominated, or Pareto optimal, if none of the objectives can be improved in value without worsening the other (Bonissone, Subbu, & Lizzi, 2009). In the context of earthwork optimization, all Pareto-optimal solutions are considered equally good and the main choice criteria for selecting one solution over the other is often decided by the project designer based on the construction final deadline and/or budget. Providing a Pareto set of optimal solutions is valuable for the construction designer, as earthworks are inherently a dynamic and thus different cost–duration solutions might become better adjusted to the ever-changing site conditions as construction develops. Moreover, additional criteria could be used to support the final decision, such as environmental aspects, which can be assessed by the determination of carbon emissions in each solution. Indeed, environmental concerns and sustainability have been a rising trend in the past few years (Chang & Tsai, 2015; Guerin, 2014; Wang, Duan, Wu, & Yang, 2014). For this reason, a flexible methodology that allows for an easy adjustment of the optimization objectives and can deal with different trade-offs is clearly advantageous.

Taking into account that Pareto front multi-optimization requires the tracking of a population of solutions, population based metaheuristics such as evolutionary multi-objective optimization (EMO), have become natural and popular solutions. Following this trend, this work adopts a popular EMO method, the non-dominated sorting genetic algorithm-II (NSGA-II) algorithm, to tackle the multi-criteria optimization problem associated with resource allocation in earthwork construction. In contrast with previous works, a true multi-objective approach is adopted, encompassing the whole earthwork construction phase and outputting a Pareto set of interesting trade-off solutions. Moreover, a novel representation of solutions is proposed, using first an EMO to allocate compaction equipment and then a linear programming to distributing the remaining equipment (e.g., excavators and trucks). Finally, the proposed system is validated by experimenting with real-world data from a construction site and compared against conventional manual earthwork design.

This paper is organized as follows. Section 2 introduces the earthworks in the context of an optimization problem, including the definition of an objective function and associated constraints. Then, Section 3 presents the adaptation of the EMO algorithm to the earthwork domain, focusing on its representation, dynamic features and algorithmic flow. Next, Section 4 details the experiments conducted and analyses obtained results when validating the proposed system using real-world earthworks data. Finally, conclusions are summarized in Section 5, which also presents future research directions.

2. Earthwork optimization

From the optimization point of view, the earthworks process can be perceived as a production line based on resources (mechanical equipment) and dependency relations between sequential tasks. The available resources can be allocated to each task in the production line, ranging from excavation and transportation to spreading and compaction equipment. Depending on the amount and type of equipment allocated and other factors, such as material type, the work rate for each task in the production line can be easily computed, since it corresponds to the sum of the work rate of assigned equipment.

Ideally, the added work rate of the equipment allocated for each task should be as close as possible to that of the equipment allocated for the next task, in order to allow a constant flow of material throughout the production line. On the one hand, this prevents idle times from incurring on the allocated equipment, in cases where the work rate of the previous task is significantly inferior to that of the succeeding task. On the other hand, in cases where the rate of the previous task is significantly superior to the succeeding task, an excessive flow of material that can ultimately obstruct movement throughout the construction site is averted. Therefore, controlling the work rate in each task within a production line is paramount. Accordingly, the main variable associated with the earthworks optimization problem is the amount of equipment allocated in each task, for each construction phase.

2.1. Problem definition

In production lines with sequential interdependent jobs, the last job determines the speed at which the whole process progresses. Considering that compaction corresponds to the last job in the earthworks production line (Fig. 1), it determines the development rate of the whole construction, thus having a direct influence on project durations. Maximizing the work rate in compaction fronts would correspond to the minimal execution duration solution, provided that there is enough equipment in the remaining tasks to support such allocation. In this point of view, an earthworks construction project is divided into a number of production lines, which correspond to the total number of compaction fronts. To each compaction front corresponds a potential production line and its associated equipment, ranging from excavation to compaction tasks. These production lines can work simultaneously and are independent from each other while progressing towards completion. However, whenever a compaction front is completed, the equipment associated with that production line becomes