Modern optimization in earthwork construction

L'optimisation moderne dans les travaux de terrassement

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ABSTRACT Earthworks tasks are often regarded in transportation projects as some of the most demanding processes. In fact, sequential tasks such as excavation, transportation, spreading and compaction are strongly based on heavy mechanical equipment and repetitive processes, thus becoming as economically demanding as they are time-consuming. Moreover, actual construction requirements originate higher demands for productivity and safety in earthwork constructions. Given the percentual weight of costs and duration of earthworks in infrastructure construction, the optimal usage of every resource in these tasks is paramount. Considering the characteristics of an earthwork construction, it can be looked at as a production line based on resources (mechanical equipment) and dependency relations between sequential tasks, hence being susceptible to optimization. Up to the present, the steady development of Information Technology areas, such as databases, artificial intelligence and operations research, has resulted in the emergence of several technologies with potential application bearing that purpose in mind. Among these, modern optimization methods (also known as metaheuristics), such as evolutionary computation, have the potential to find high quality optimal solutions with a reasonable use of computational resources. In this context, this work describes an optimization algorithm for earthworks equipment allocation based on a modern optimization approach, which takes advantage of the concept that an earthwork construction can be regarded as a production line.

RÉSUMÉ Les travaux de terrassements sont souvent considérés dans les projets d'infrastructure de transport comme un des processus les plus exigeants. En effet, des tâches séquentielles comme l'excavation, le transport, le régalage et le compactage sont fortement basées sur des équipements mécaniques lourds et des processus répétitifs, dont leur ampleur économique, étant donnée aussi le temps de réalisation. En outre, la construction actuelle est plus exigeante au niveau de la productivité et la sécurité dans les travaux de terrassements. Compte tenu du poids relatif des coûts et de la durée des travaux de terrassement dans les projets de construction d'infrastructures, l'utilisation optimale de toutes les ressources allouées à ces tâches est primordiale. Dans ce contexte les différentes phases des travaux de terrassements peuvent être considérées comme une ligne de production basée sur les ressources (équipement mécanique) et les relations de dépendance entre les tâches séquentielles et donc être susceptible d'optimisation. Jusqu'à présent, le développement des technologies de l'information, comme les bases de données, l'intelligence artificielle et la recherche opérationnelle, a donné lieu à l'émergence de plusieurs technologies applicables à ce bout. Parmi celles-ci, les méthodes modernes d'optimisation, tels que les algorithmes génétiques, sont mises en évidence en raison de leur fiabilité et aussi du réduit effort de calcul. Dans ce contexte, ce travail décrit un algorithme d'optimisation d'affectation de l'équipement de terrassements sur la base des approches d'optimisation modernes, tenant au compte l'idée selon laquelle les travaux de terrassement peut être considérée comme une ligne de production.

1 INTRODUCTION

In Civil Engineering, earthworks are tasks aimed to create or improve foundation conditions, which will be able to support the construction of structural elements. Comprised of sequential tasks strongly based on heavy mechanical equipment and repetitive processes, such as excavation, transportation, spreading and compaction, earthworks are often regarded in transportation projects as some of the most economically demanding and time-consuming processes. Simultaneously, present construction concerns originate higher standards for productivity and safety in this type of constructions. Given the percentual weight of costs and duration of earthworks in infrastructure construction projects such as roads, railroads and airports, the optimal usage of every resource in these tasks is paramount.

Optimization attempts in the context of earthworks falls mostly under the category of resource selection and allocation, in which resources are represented by the mechanical equipment, with the objective of minimizing both execution duration and costs. As one can infer, there is an infinity of possible design solutions for allocating the selected equipment throughout the earthworks project. Furthermore, as conflicting objectives, each solution implies a trade-off in terms of total duration and costs. However, in most cases contractors and project designers often settle for a random trade-off, mostly based on their own experience. Obviously, the resulting allocation solutions do not guarantee minimal final costs and durations.

As such, an innovative method for optimally allocating the earthworks equipment throughout construction phases is necessary. In this context, the steady development of Information Technology areas, such as databases, artificial intelligence and operations research, has resulted in the emergence of several technologies with potential application for the optimization of earthworks. Among these, modern optimization methods (also known as metaheuristics), such as evolutionary computation (F. Cheng et al. 2010; T. Cheng et al. 2005; Kataria et al. 2005; Marzouk & Moselhi 2002; Nassar & Hosny 2012; Xu et al. 2011; Zhang 2008), have the potential to find high quality optimal solutions with a reasonable use of computational resources. Nevertheless, most existent applications focus on optimizing or modelling single tasks or part of the process (i.e. excavation or loading and hauling), neglecting the advantages of an integrated and global optimization.

In this framework, this work describes a multi-objective optimization algorithm for earthworks equipment allocation based on modern optimization techniques, which minimizes both earthwork execution costs and durations. The paper is divided into five sections, including this introduction followed a background of earthworks from an optimization point of view in Section 2. Section 3 shows how a modern optimization algorithm can be adjusted to the problem, featuring the developed algorithm. Lastly, some results regarding the validation of the algorithm for an earthworks construction case are presented in Section 4, which lead to the conclusions drawn in Section 5.

2 EARTHWORKS ALLOCATION: PROBLEM DEFINITION

Considering the characteristics of an earthwork construction, it can be looked at as a production line based on resources (mechanical equipment) and dependency relations between sequential tasks, hence being susceptible to optimization. Allocating several pieces of equipment to a single task in a production line will increase the total equipment work rate for that task. However, the maximum number of equipment allocated for a single task is limited by the available equipment and site conditions, such as space restrictions in excavation or compaction fronts.

When dealing with sequential interdependent tasks such as these, the speed at which a single production line can carry out its work is equivalent to the work rate associated with its last task. In this context, maximizing the work rate in the final task (in this case, compaction) would correspond to a solution with minimum execution time for a production line. However, such allocation is always function of the available equipment. So as to fully take advantage of the available resources, one must guarantee that the allocated compaction equipment is fed enough material so as to allow for constant production. In other words, the work rate in all tasks prior to compaction (excavation, transportation and spreading) must be equal or similar to the work rate obtained in the associated compaction front. In fact, for any given task, if the work rate of the task that precedes it is inferior to its own, then the productivity of the task in question will be limited by it. Should this happen, the designer is keeping the equipment from reaching its maximum possible work rate, and thus wasting the full potential of the allocated resources (e.g. by incurring in equipment idle times). This implies that the total work rate of a production line is equivalent to the minimum work rate from the individual tasks that comprise it. Therefore, controlling the work rate in each task within a production line is paramount.

Naturally, an earthwork construction is not depicted in a single production line, but rather in several independent production lines working simultaneously. Each of these production lines is associated with a compaction front, onto which material is transported by transportation equipment (e.g. dumper trucks). However, it should be mentioned that, for a given equipment allocation throughout several production lines, eventually one of these production lines will conclude its compaction work. At this point, the material associated with that production line is no longer contributing towards the completion of the earthwork project, thus calling for its reallocation into a new production line. As site conditions have changed since the previous allocation, the optimal way to carry on this reallocation should include all available equipment once again, thus reorganizing the whole resource plant in order to resume the execution of the project. This enhances the problem with a dynamic feature, which must be taken into consideration in any optimization attempt.

3 MODERN OPTIMIZATION IN EARTHWORKS EQUIPMENT ALLOCATION

Several modern optimization technologies have been applied to earthworks optimization. In general, the most effective applications for direct optimization of resources in earthworks are based on modern optimization techniques, such as genetic algorithms (GA) (Marzouk & Moselhi 2002; Moselhi & Alshibani 2007; Xu et al. 2011) or swarm intelligence (Kataria et al. 2005; Miao et al. 2011; Nassar & Hosny 2012; Zhang 2008). Yet, most applications are either focused on modelling and parameter estimation of single tasks at a specific instant, or optimization of partial earthwork processes, as is the case with excavation and hauling. For this reason, these systems lack the advantages of a global optimization of execution durations and costs throughout all construction phases. Indeed, attempting to minimize these objectives by optimizing individual tasks or construction phases oversimplifies the problem and might not return optimal results. For instance, such representation is not able to consider the advantages of allocating additional equipment to a task in a specific construction phase, which may be advantageous in terms of global duration and cost, even though the cost for that specific task increases.

These modern optimization techniques, namely GA (Holland, 1975), come forward as some of the most effective optimization tools, on account of their efficiency when dealing with extensive search spaces within reasonable computational effort, as well as their ease of interpretation and implementation. Based on artificial intelligence and natural selection processes, GA start by generating random solutions for a problem, which are iteratively improved, tending towards optimal or near-optimal solutions. With this in mind, by interpreting the problem as a series of production lines, it becomes possible to focus the GA's allocation of resources to the compaction task (last task of the production lines), which sets the work rate target value for each production line. The algorithmic flow for the multi-objective GA and its associated fitness function is shown in Figure 1. The objective is achieved using a specific chromosomal representation, which initially distributes the compaction equipment for all necessary construction phases in a random way. Having an initial distribution of compactors, the equipment for the remaining tasks (excavation, transportation, spreading) is then distributed by using linear programming (LP) optimization models, targeting the minimization of cost while restricting the minimum required work rate to that of the associated compaction front. In each solution, this process is repeated for each construction phase, resulting in a determination of global costs and durations for the initial distribution of compaction equipment. The best solutions are then subjected to GA operators, namely crossover and mutation, generating new solutions which are evaluated using the same methodology. This architecture falls into the framework proposed in (Parente et al. 2014; Parente et al. 2015).

4 SOME PRELIMINARY OPTIMIZATION RESULTS

Preliminary validation tests have been carried out in order to assess the functionality and advantages of the developed optimization system. The validation was carried out using as a reference an equipment allocation database concerning a road construction in Portugal (Parente et al. 2014).

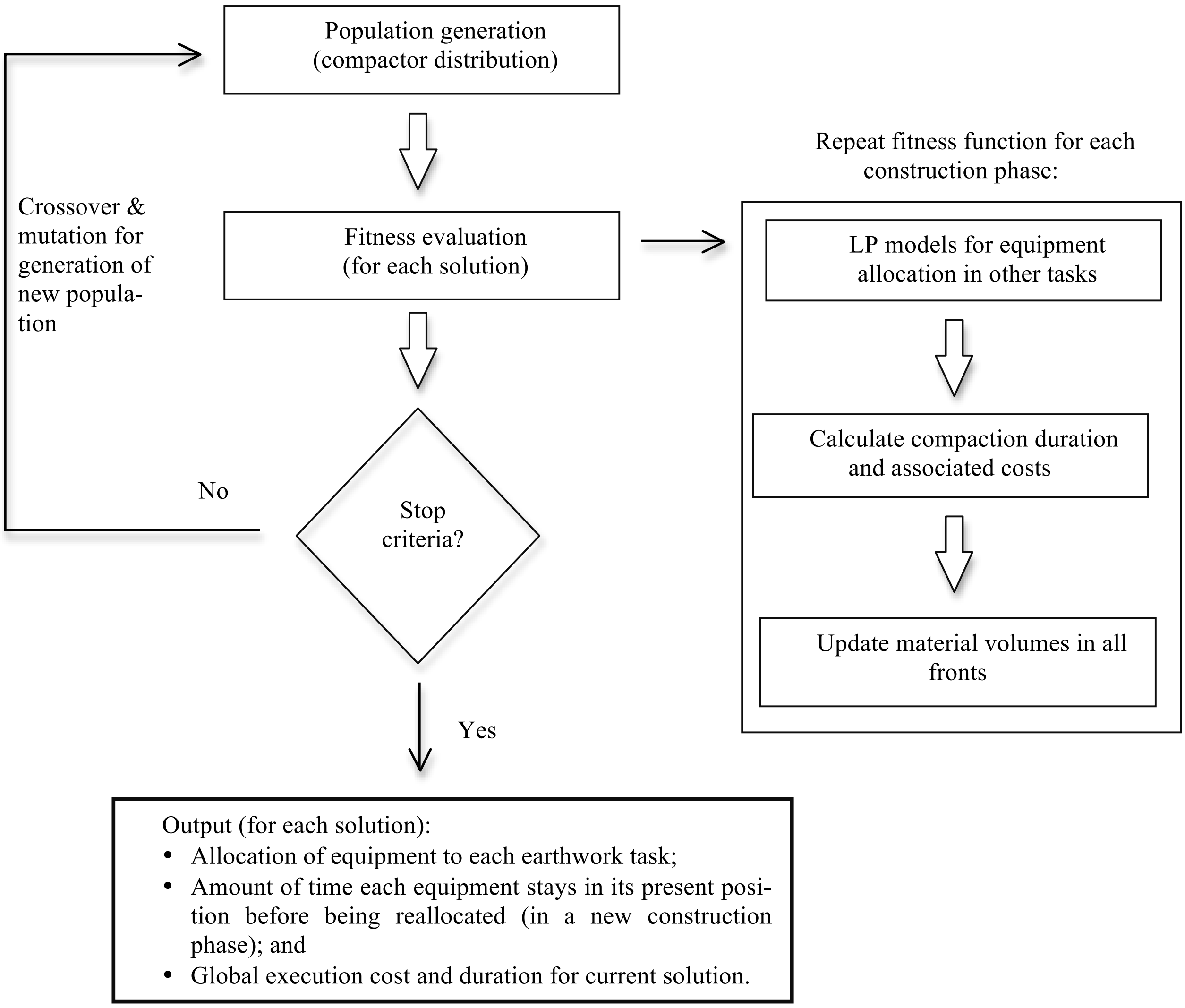

Figure 1. Algorithmic flow for the optimization system

The available data includes the daily allocation of earthwork equipment throughout a road construction site. The equipment in this data was originally distributed throughout earthwork tasks by conventional design methodologies.

Table 1 intends to exemplify some of the obtained results obtained by modelling and optimizing a specific production line. In this optimization attempt, the equipment available for the conventional design was kept fixed. In other words, the presented results stem from a simple reorganization of the available equipment throughout the construction fronts, without the addition of any other piece of equipment, using the optimization methodology presented in Section 3.

It is possible to infer from the analysis of Table 1 that the allocated excavator equipment represents a bottleneck for the production line in the original allocation solution. Considering that excavation is being carried out in the same front in both the original and the optimized setups, both the transportation distance and the transported material type are the same. Concurrently, the same roller was picked in both setups, which have the same potential maximum work rate, since the same material is being compacted. Different types of spreaders were allocated in these setups. Although the potential spreader work rate in the original setup is only slightly lower than the compaction work rate, the system considered that a larger and heavier bulldozer was necessary so as to prevent any limitation to the compaction workflow. Up to this point, both the original and the optimized setup are very similarly allocated in terms of allowing a constant flow of material throughout the production line. However, one can see that dumper trucks and excavators in the original setup are not well adjusted to the rest of the production line. Regarding the former, the number of dumper trucks seems to be overestimated (having a maximum potential work rate of 1280 m^3/h), bearing in mind the potential maximum work rate of the succeeding tasks (683 and 675 m^3/h for compaction and spreading operations, respectively). It is noteworthy to emphasize that the hourly work rate of a single dumper truck is a function of not only on its capacity, but also the distance of the trips between excavation and compaction fronts. However, the original allocation solution yields increased execution costs, but not decreased durations, when compared with the optimized setup. In fact, neither the allocated excavators nor spreaders are capable of keeping up the same pace as the dumper truck team. As one can see, this does not happen in the optimized setup, where just enough dumper trucks were allocated so as to keep a constant flow of material throughout the production line. In the case of excavators, it is easy to infer how the choice and/or number of excavators are limiting the whole production line in the original setup. In this solution, the original production line cannot operate at a work rate higher than 540 m^3/h, significantly hindering the compactor work rate, which are only working at about 75% of its maximum potential work rate. Such setup neither guarantees minimal durations, nor embodies a good solution in terms of costs and environmental aspects, since the low work rate at the start of the production line will incur in idle time by the equipment in the succeeding tasks. This will ultimately waste fuel, mechanical and manpower resources and increase unnecessary carbon dioxide emissions.

Table 1. Comparison between the conventional allocation and the optimized allocation

Parameter	Conventional allocation	Optimized allocation
Approximate distance to excavation front (m)	500	
Number of compactors	1	1
Compactor work rate (m^3/h)	683	683
Number of spreaders	1	1
Spreader work rate (m^3/h)	675	820
Number of dumper trucks	3	2
Dumper truck work rate (m^3/h)	1280	880
Number of excavators	1	2
Excavator work rate (m^3/h)	540	743

As mentioned, this lack of adjustment regarding work rates in successive tasks can be observed in several production lines in the original setup. It is probably a result of a standardization of teams by part of the contractor. Indeed, the data seems to indicate that a standard team of 1 roller, 1 spreader, 3 dumper trucks and 1 excavator is considered for most cases, which does not correspond to the optimal solution in many of them, as previously discussed. The results obtained by modelling and optimization of several phases using this methodology indicate that it would be possible to reduce execution times for some of the construction phases between 20 to 50% of their original duration, without increasing costs. This simultaneously emphasizes the importance of optimization in this type of construction and shows how the conventional allocation methodologies can be relatively counter-productive.

5 CONCLUSIONS

In constructions where earthworks activities are a significant percentage of total execution durations and costs, such as road, railway or airport constructions, the optimization of all available resources is vital. However, conventional resource allocation methodologies are not equipped to properly optimize the available equipment resources.

This paper presents a methodology to guarantee the optimization of resources in earthwork constructions, in the form of an optimization system for the minimization of execution durations and costs. The system is based on a genetic algorithm, supported by linear programming models, which attempts to guarantee that every allocated equipment is working at its full potential, thus avoiding equipment idle time.

Some preliminary results aiming to validate the optimization system using a real earthwork construction database were presented. These emphasize the importance of optimization in this type of construction. Simultaneously, some flaws in conventional resource allocation methodologies were exposed, which can be overcome by the system.

Naturally, however, during execution of earthwork projects, unpredictable events are constantly occurring (e.g. arriving at a conclusion that the material does not have the expected quality, equipment malfunction), which are not taken into account by the optimization system. These issues can be tackled by successively updating the optimization model as construction carries on, allowing the system to reallocate available resources in order to adapt to the new conditions.

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