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Transportation Research Procedia 14 (2016) 3601 – 3610

Transportation Research Procedia

www.elsevier.com/locate/procedia

6th Transport Research Arena April 18-21, 2016

A novel integrated optimization system for earthwork tasks

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Abstract

Earthworks are part of the construction of any type of ground transport infrastructure. In many road and railway infrastructures earthworks represent up to 30 to 50% of total cost of the construction. Moreover, earthworks involve the use of heavy mechanical equipment (e.g., excavators, dumper trucks, bulldozers and rollers) and repetitive activities that are responsible for large amounts of carbon emissions with negative impact to the environment.

In this context, the optimization of earthworks construction activities is becoming increasingly important in recent years, while effective and practical integrated solutions have not been established so far. As such, this work introduces a novel optimization integrated system for earthwork tasks. In this integrated system, the optimization is carried out on various fronts, namely minimization of execution cost and duration, while attempting to reduce environmental impacts, such as carbon emissions. In order to achieve this, the integration of a wide array of technologies is required, so as to allow for a proper adjustment to reality. These range from evolutionary computation and data mining (i.e., soft computing), to geographic information systems and linear programming. The former are used firstly to provide realistic estimates of the productivity of available resources (i.e., equipment), and secondly to perform their optimal allocation throughout the construction site. Concurrently, the latter are employed for supporting the optimization of resource and material management, as well as of the trajectories associated with transportation of material from excavation to embankment fronts.

The system has been validated using real-world data stemming from a Portuguese road construction site. Results show that the proposed system is very competitive when compared with the manual allocation methodologies currently used for the design and construction of earthworks. In fact, the system can output several different resource distribution solutions, which comprehend a trade-off between the referred optimization objectives, enhancing the flexibility of design by allowing the user to select the solution that best fits the project restrictions (e.g., deadline, budget). As such, the system is capable of allocating the available

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Peer-review under responsibility of Road and Bridge Research Institute (IBDiM)
doi:10.1016/j.trpro.2016.05.428

equipment in a way that maximizes its potential and productivity, while indirectly guaranteeing minimum carbon emissions in each possible solution. These results emphasize the importance of using this kind of decision support/optimization tools in the design and construction of earthworks.

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Keywords: earthworks; optimization; carbon emissions; soft computing; geographic information systems; linear programming

1. Introduction

In many road and railway infrastructures earthworks represent up to 30 to 50% of total cost of the construction. Moreover, earthworks involve the use of heavy mechanical equipment (e.g., excavators, dumper trucks, bulldozers and rollers) and repetitive activities that are responsible for large amounts of carbon emissions with negative impact to the environment. In this context, the optimization of earthworks construction activities is becoming increasingly important in recent years, while effective and practical integrated solutions have not been established so far.

Taking into account the optimization point of view, earthwork construction can be described as a number of production lines based on resources and dependency relations between sequential tasks. The resources correspond to the aforementioned mechanical equipment, while the sequential tasks comprise the associated processes, specifically excavation, transportation, spreading and compaction, respectively. While there are some characteristics common to all production line problems, the earthworks optimization includes some specific characteristics, which add to its complexity. In the former category, sequentiality and interdependency are noteworthy, as they define the optimization approach itself. Indeed, besides the fact that earthwork tasks must be carried out in a specific sequence (e.g., excavation, transportation, spreading, compacting), the productivity in each of those tasks is dependent on the productivity associated with the preceding tasks. In other words, a task with a very low productivity will work as a bottleneck to the remaining production line tasks, keeping the allocated equipment from reaching its maximum productivity potential, e.g. forcing a dumper truck team to incur in idle time while waiting for material to be excavated. This means that optimizing earthworks must also take into account the homogeneity of productivity between the tasks that comprise the process. Regarding the characteristics specific to earthwork production line problems, one must bear in mind that, in an earthworks construction site, there will be not only one, but several production lines working simultaneously. At this point in time when one of those production lines completes its excavation/embankment work, the associated resources become idle, requiring their redistribution to other work fronts in order to allow for the development of the project. This represents a change in the optimization conditions of the earthworks project, which will naturally occur several times up to its completion, classifying this problem as dynamic. As such, bearing in mind the optimization conditions in this problem are time-evolving, the associated solution must be time-evolving as well. In order to deal with this issue, an unique solution representation is required.

This work introduces a novel optimization integrated system for earthwork tasks. In this integrated system, the optimization is carried out on various fronts: minimization of execution cost, duration, and environmental impacts, such as carbon emissions. In order to achieve this, the integration of a wide array of technologies is required, so as to allow for a proper adjustment to reality. These not only include different optimization technologies, such as evolutionary computation and linear programming, but also other technologies which are required to support the optimization process, like data mining and geographic information systems. While the former comprise the foundation for the optimization procedure, the latter are used to support that procedure by accurately estimating unknown optimization parameters (e.g. equipment productivity). Although there have been some earthworks optimization applications using evolutionary computation (F. Cheng, Wang, & Ling, 2010; T. Cheng, Feng, & Chen, 2005; Kataria, Samdani, & Singh, 2005; Marzouk & Moselhi, 2002; Nassar & Hosny, 2012; Xu, Wang, & Xia, 2011; Zhang, 2008), attempting to optimize partial aspects of the process, as well as some data mining applications (Edwards & Griffiths, 2000; Hola & Schabowicz, 2010; Parente, Gomes Correia, & Cortez, 2014; Schabowicz & Hoła, 2008; Shi, 1999; Tam, Tong, & Tse, 2002), mainly for estimating task duration, productivity or cost in earthworks, these do not attempt to solve the global earthworks optimization problem (i.e. taking into account all tasks and dependency relations). Moreover, even though these soft computing technologies (i.e. evolutionary computation and data mining) have complementary strengths for the earthworks case, there are no applications that integrate them into a single system.

The system has been validated using real-world data stemming from a Portuguese road construction site. Results show that the proposed system is very competitive when compared with the manual allocation methodologies currently used for the design and construction of earthworks. In fact, the system can output several different resource distribution solutions, which comprehend a trade-off between the referred optimization objectives, enhancing the flexibility of design by allowing the user to select the solution that best fits the project restrictions (e.g., deadline, budget, carbon emissions). Moreover, the system is capable of not only allocating the available equipment in a way that maximizes its potential and productivity, but also of keeping a tight control over carbon emissions in each possible solution. These results emphasize the importance of using this kind of decision support/optimization tools in the design and construction of earthworks.

The paper is organized as follows. Firstly, a brief description of evolutionary computation and data mining technologies, including a short review of their applications to the earthwork domain, is described in Section 2. Secondly, the multi-criteria optimization system is detailed in Section 3, featuring the description of the system and results that were obtained when applying such system with real-world data from a construction site in Portugal. Finally, conclusions are presented in Section 4.

2. Technologies for the optimization of earthworks

Considering the non-linear characteristics of the earthworks optimization problem, and since it includes a large search space (in terms of distribution combinations of equipment throughout the construction site in each phase), conventional Operational Research (e.g. linear programming) and blind search methods alone are not effective for solving this problem. As such, evolutionary computation are an interesting solution within this domain, since they are capable of searching interesting search space regions under a reasonable use of computational resources.

Among these, genetic algorithms (GA) have been established as one of the most well adjusted algorithms regarding the earthworks allocation problem (T. Cheng et al., 2005; Kataria et al., 2005; Marzouk & Moselhi, 2002; Xu et al., 2011; Zhang, 2008). GA consist of stochastic algorithms whose search methods model natural phenomena, such as genetic evolution and the concept of Darwinian natural selection. A GA creates a population of random initial solutions and applies genetic operators such as mutation and crossover to evolve the solutions in order to find the best one (Fig. 1). In each phase of the GA process, each individual is evaluated in terms of fitness (depending on the selected evaluation mechanism and the objectives of the problem), allowing the ones with higher fitness to have a better chance of being selected as parents to generate new individuals (new population, also referred to as descendants), by means of processes like crossover and mutation (Holland, 1975).

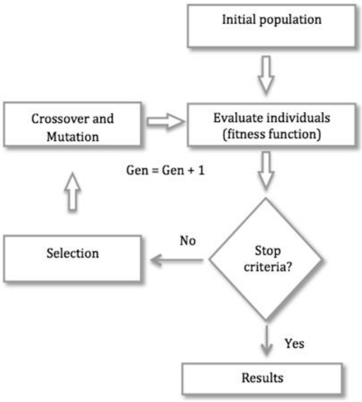


Fig. 1. GA algorithmic flow (adapted from Holland, 1975).

However, considering that the quality of an earthworks project design can only be as good as the ability to estimate the associated equipment productivity as close to reality as possible, optimization methods alone are not enough to guarantee a good earthworks design. In this context, data mining (DM) provides an interesting approach for estimating productivity parameters. DM is usually considered part of a larger process known as knowledge discovery in databases (KDD) (Fayyad, Piatetsky-Shapiro, & Smyth, 1996), which corresponds to the process of analyzing large databases for patterns and trends in data in order to infer rules for them (Fig. 2). These rules are turned into knowledge, which can be used to predict future values in new environments and for a better understanding of the problem domain variable relationships. Guided by domain knowledge and under a semi--automated process that uses computational tools, DM is an iterative and interactive process. Some popular predictive DM models have been applied to earthworks with different goals, such as estimation of productivity parameters (Parente et al., 2014; Schabowicz & Hoła, 2008; Shi, 1999; Tam et al., 2002) or execution duration and cost (Edwards & Griffiths, 2000; Hola & Schabowicz, 2010).

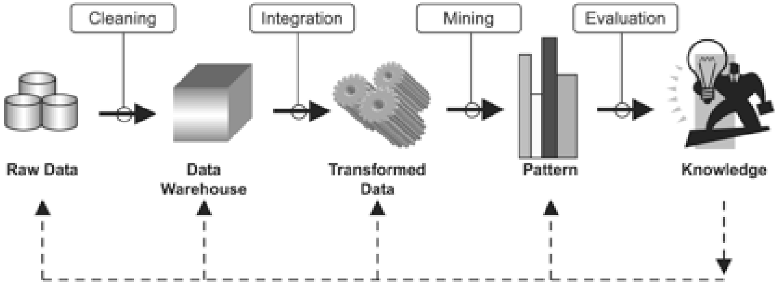


Fig. 2. KDD process (Fayyad et al., 1996).

3. Earthworks optimization system

3.1. Architecture

Following up on previous work (Gomes Correia & Magnan, 2012), the developed system is comprised of a DM module and a GIS module, which support the multi-objective optimization of equipment allocation in earthworks. This translates into three integrated modules (equipment, spatial and optimization modules), with capabilities to acquire and manipulate data from each phase of an earthwork project. Table 1 summarizes the modules and their functions, while Figure 3 depicts their interaction and the flow of information in the system.

Table 1. Modules, technologies and functions.

Module	Technology	Function
Equipment	Data mining	• User inputs • Estimation of equipment productivity
Spatial	Geographic information systems	• Modeling of construction site • Path finding for transportation equipment
Optimization	Evolutionary computation	• Optimal selection and allocation of equipment fleet • Return output to user

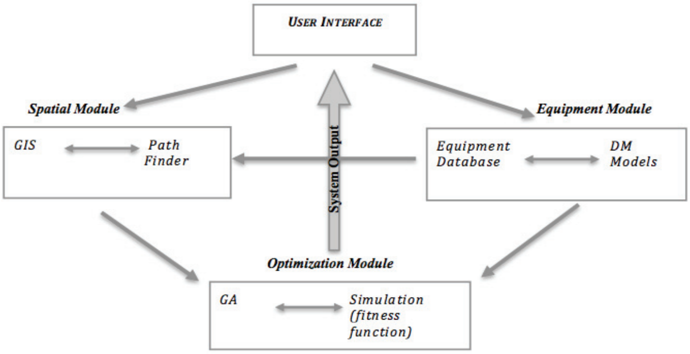
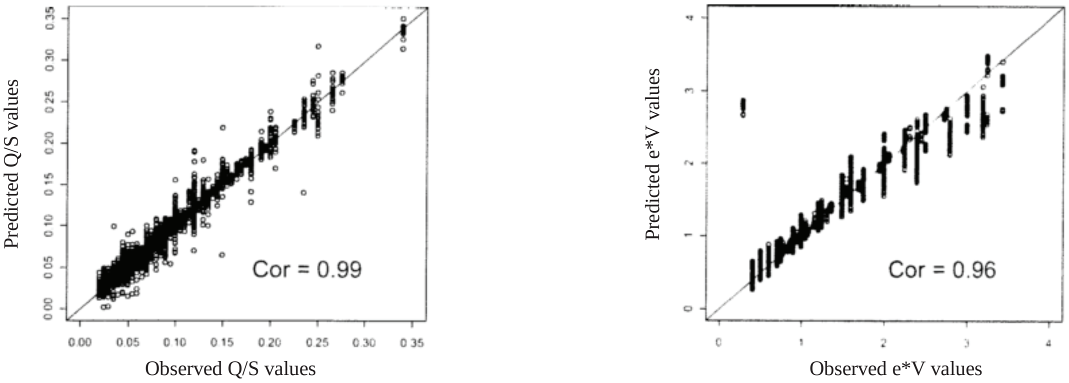


Fig. 3. Proposed system architecture.

The equipment module is responsible for receiving the user input for available equipment/plants, while calculating or retrieving equipment costs. Simultaneously, this module should be able to accurately determine the productivity rates for available equipment. To achieve this goal, a previously developed data-driven model (Cortez, Marques, & Gomes Correia, 2008) based on the application of DM to a compaction database from the Guide the Terrassements Routiers (GTR) (SETRA & LCPC, 2000), a broadly used and well-known compaction guide, was used. In this model, a series of neural networks are applied to data stemming from the GTR compaction tables, with the purpose of predicting several compaction parameters, as a function of the material to be compacted, the state conditions and energy of compaction. Figure 4 depicts the performance of the DM models regarding the prediction of two of these parameters (i.e. elementary thickness – a thickness of a given geomaterial that can be compacted in a roller application to obtain the desired density – Q/S, and an value of layer thickness times roller speed, e*V, respectively), showing an excellent level of adjustment and predictive capability. Having gathered the knowledge of these parameters, it is easily to calculate the theoretical productivity (Q/L) value for each compactor-geomaterial pair.

$$Q/L = 1000 \times (Q/S) \times V \tag{1}$$

where: Q is the volume of compacted geomaterial during a given time (in m^3/h), S is the surface compacted under the same time (in m^2/h), L is the width of the roller (in m), and V is the velocity of the roller (in km/h).



a)

b)

Fig. 4. Predicted values vs. observed values for: a) Q/S parameter; b) e*V value (Cortez et al., 2008).

The spatial module is founded upon GIS technology. On the one hand, its primary purpose is to gather the necessary information, generated from spatial data, to assist the proper optimization of transportation equipment distribution and workflow. This data is associated with the optimal routes, distances and cycle times between excavation and embankment fronts, as well as with spatial models of earthwork construction sites, which include information regarding the relative positioning between fronts and the possible routes that connect it (Fig. 5). On the other hand, the spatial module is expected to provide a basis for spatial input and output visualization, enhancing the system with the possibility of receiving GPS data (if available) during construction phase of earthwork projects. This allows the system to automatically update the actual productivity of the equipment during work, and adjust itself in real-time as the construction process goes on in order to keep the optimal status of the equipment allocation. Considering the dynamic and hard-to-predict nature of earthwork projects during construction, these features add the necessary versatility to the system to deal with unforeseen events or problems.

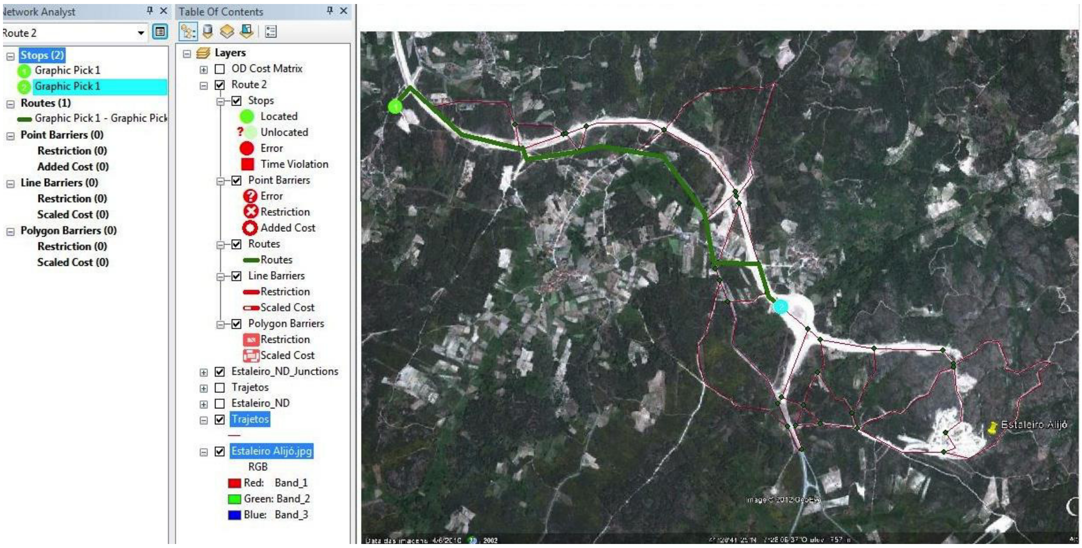


Fig. 5. Optimization of truck routes.

The information flow from the previous modules converges on the optimization module. Having gathered the required information from the equipment and spatial modules to support the optimization process, this module attempts to find an optimal solution in terms of the best possible equipment fleet and its optimal distribution throughout the work area. Bearing in mind the sequentiality and interdependency characteristics of an earthworks production line, one of the most important aspects to guarantee the usage of resources to their maximum potential is the prevention of bottlenecks in the allocated production lines. In order to achieve this, the allocation is initially focused on the compaction equipment only (i.e. associated with the last task of the production line). By adopting this approach, it becomes possible to the equipment associated with the remaining tasks in function of the productivity that has been allocated in the embankment fronts (i.e. compaction teams), guaranteeing that the productivity in each task is equals or above that value. This last step is included inside the fitness function, after using the DM models to accurately estimate the productivity of the allocated compactors. After the best solutions have been considered and evaluated, the Optimization Module presents the user with the best-found solutions through the user interface as the output for the system. Figure 6 depicts the optimization algorithm, including the imported data from the equipment and spatial modules.

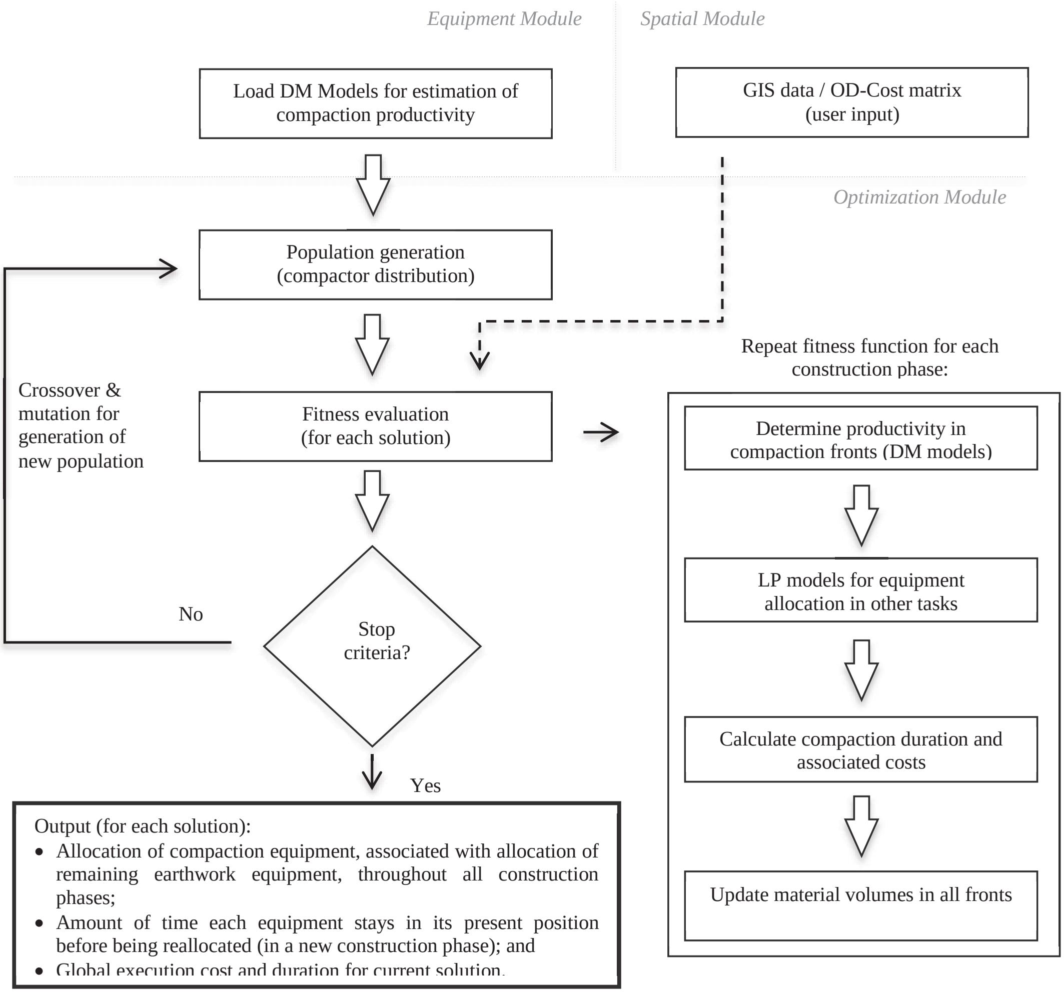


Fig. 6. Integrated optimization system algorithmic flow.

3.2. Case study results

This novel system was applied to a database created from the earthworks of a Portuguese highway construction site. The original database includes the description of several years of earthworks construction, broke down into the daily activities of the available mechanical equipment. In this application, the data subset regards the activities of earthwork equipment throughout 6 months of construction phase, featuring around 1250 entries (after data preparation) with information on date, work hours, atmospheric conditions, number and distance of load trips and resource types for each piece of mechanical equipment used in the construction process.

The purpose of the optimization system for this case was to determine the solution that minimized both cost and duration for the whole earthwork construction process. It should be highlighted that, in this application, the equipment allocated by the optimization system is exactly the same that was available for the conventional design allocation (i.e. the original solution). 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.

As previously mentioned, an ideal distribution solution must take into account the interaction between the different types of equipment that encompass the earthwork production line, so as to avoid productivity bottlenecks. This aspect is very challenging to achieve in conventional earthworks design, as can be seen in Table 2. Analyzing this table reveals that the work rates in each task of the original distribution setup are not homogeneous, as opposed to the work rates of the optimized solution. As such, in this case, the productivity of the excavator team represents a bottleneck in the original solution. This means that the equipment in succeeding tasks will incur in idle time while waiting for material to be ready for handling, which represents wastes in terms of resources (since these do not work at full efficiency) and fuel (contributing to unnecessary costs), as well as an increase on unnecessary carbon emissions. In contrast, the work rates obtained in the proposed optimized solutions for each task that comprises the earthwork process are as homogeneous as possible, given the available equipment. As such, a constant flow of material throughout tasks can be achieved, using the allocated resources to their full potential.

Table 2. Comparison of productivity in each task between the original and the optimized allocation solutions.

Parameter	Original solution	Optimized solution
Average distance to excavation fronts (m)	175	
Number of Compactors	1	1
Compactor work rate (m^3/h)	614	1055
Number of spreaders	1	2
Spreader work rate (m^3/h)	413	1239
Number of dumper trucks	2	2
Dumper truck work rate (m^3/h)	2960	1600
Number of excavators	1	2
Excavator work rate (m^3/h)	394	1080

By using this methodology, the system was able to achieve a high impact in both construction cost and duration for this case-study. Figure 7 illustrates the output of the system in the form of a Pareto front. In this figure, each point represents a feasible and optimal equipment distribution solution for the earthworks project, evaluated in terms of its associated duration (in hours) and cost (in euro). The system output presents several solutions ranging from approximately 32 to 42 hours of construction duration, associated with approximate costs of 40,000 € to 47,000 €, respectively. This corresponds to a reduction of around 50% to 70% in cost and duration, when compared to the duration of 127 h and cost of 135,200 € that was obtained in the original allocation. Additionally, this type of output is flexible enough to allow the designer to select the solution that best fits the current project restrictions (i.e., budget and deadlines), which represents another advantage when compared with conventional design.

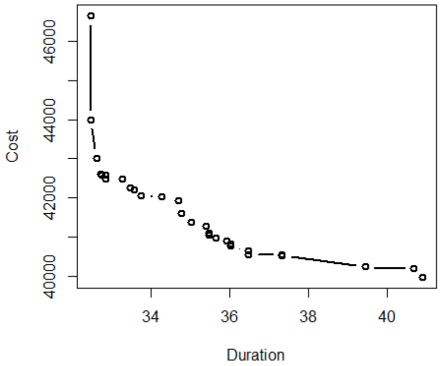


Fig. 7. Output associated with one run of the optimization system for the case-study (*x*-axis in hours, and *y*-axis in €).

4. Conclusions

Bearing in mind how earthworks comprise a high percentage of costs and durations in many Civil Engineering projects, namely road, railway and airport construction, their optimization should always be a priority. Given this, any reduction on that percentage will have a significant effect on the final cost and duration of the whole construction project. In this context, conventional manual design, often based on experience and intuition, is limited. Moreover, current intelligent automated applications often target single tasks or partial processes that comprise earthworks and do not simultaneously optimize both cost and duration goals.

The novel system proposed in this work was applied in a case study using real-world data from a Portuguese construction site, showing that it is quite competitive when compared with conventional design, and that it can be easily adapted to dynamic changes that are inherent to earthworks constructions. In fact, for this case study, a high impact on would be achieved by the implementation of this system, as results indicate a reduction of approximately 50% in construction cost and duration when compared with the originally adopted solution (achieved via conventional manual design). Naturally, these results do not take into account the possible delays and costs associated with unpredictable events and obstacles that occur during construction (e.g., equipment malfunction). However, the system features the flexibility to deal with these issues, since it allows for the user to easily rerun the optimization procedure with an updated set of conditions and constraints (e.g., less available equipment), which outputs a new set of optimal allocation solutions.

The computational experiments not only bring forth the potential of the system, but also identify some significant of the limitations of conventional manual earthworks design, in particular where the production line equipment is either significantly above the required work rate requirements (incurring in unnecessary costs) or below it (resulting in idle times and low efficiency ratios). Moreover, it was possible to verify the capability of the proposed system to distribute equipment in a relatively homogeneous way (when compared to conventional design), while minimizing costs and durations, which was one of the goals of this research.

Future work will concern the expansion of the modelling capabilities of the system. This aims to take into account aspects like loading and dumping configurations, or space optimization in work fronts (e.g., where to place machinery in a work front, so as to facilitate and maximize the interaction between equipment) for a further comprehensive and integrated optimization. Moreover, bearing in mind the increasing importance of sustainability in construction in recent years, it is imperative to explore the potential development of a new module (or the enhancement of the already developed modules) towards taking this aspect into account. The module should be able to objectively determine the sustainability index associated with an earthwork project, accounting, for instance, for carbon emissions and material treatment procedures.

Acknowledgements

The authors wish to thank FCT for the financial support under the project UID/ECI/04029/2013.

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