Metaheuristics, Data Mining and Geographic Information Systems for Earthworks Equipment Allocation

Manuel Parente[1*], António Gomes Correia, Paulo Cortez[2]
[1]*ISISE – Institute for Sustainability and Innovation in Structural Engineering, University of Minho, Portugal*
[2]*ALGORITMI Research Centre, University of Minho, Portugal*
map@civil.uminho.pt, agc@civil.uminho.pt, pcortez@dsi.uminho.pt

---

Abstract

Optimal and sustainable allocation of equipment in earthwork tasks is a complex problem that requires the study of several different aspects, as well as the knowledge of a large number of factors. In truth, earthworks are comprised by a combination of repetitive, sequential, and interdependent activities based on heavy mechanical equipment (i.e., resources), such as excavators, dumper trucks, bulldozers and compactors. In order to optimally allocate the available resources, knowledge regarding their specifications (e.g., capacity, weight, horsepower) and the work conditions to which they will be subjected (e.g., material types, required and available volumes in embankment and excavation fronts, respectively) is essential. This knowledge can be translated into the productivity (i.e., work rate) of each piece of equipment when working under a specific set of conditions. Moreover, since earthwork tasks are inherently sequential and interdependent, the interaction between the allocated equipment must be taken into account. A typical example of this is the need for matching the work rate of an excavator team with the capacity of a truck team to haul the excavated material to the embankment fronts.

Given the non-trivial characteristics of the earthwork allocation problem, conventional Operation Research (e.g., linear programming) and blind search methods are infeasible. As such, a potential solution is to adopt metaheuristics – modern optimization methods capable of searching large search space regions under a reasonable use of computational resources. While this may address the issue of optimizing such a complex problem, the lack of knowledge regarding optimization parameters under different work conditions, such as equipment productivity, calls for a different approach. Bearing in mind the availability of large databases, including in the earthworks area, that have been gathered in recent years by construction companies, technologies like data mining (DM) come forward as ideal tools for solving this problem. Indeed, the learning capabilities of DM algorithms can be applied to databases embodying the productivity of several equipment types when subjected to different work

---

[*] Corresponding author.

conditions. The extracted knowledge can then be used to estimate the productivity of the available equipment under similar work conditions. Furthermore, as previously referred, since earthwork tasks include the material hauling from excavation to embankment fronts, it also becomes imperative to analyze and optimize the possible transportation networks. In this context, the use of geographic information systems (GIS) provides an easy method to study the possible trajectories for transportation equipment in a construction site, ultimately allowing for a choice of the best paths to improve the workflow.
This paper explores the advantages of integrating the referred technologies, among others, in order to allow for a sustainable management of earthworks. This is translated in the form of an evolutionary multi-criteria optimization system, capable of searching for the best allocation of the available equipment that minimizes a set of goals (e.g., cost, duration, environmental impact). Results stemming from the validation of the resulting system using real-world data from a Portuguese construction site demonstrate the potential and importance of using this kind of technologies for a sustainable management and optimization of earthworks.

Keywords: earthworks, optimization, sustainability, metaheuristics, data mining, geographic information systems

1 Introduction

Following the current research and innovation trends, including the EU 2020 Horizon goals, sustainable construction has been the subject of increased attention in recent years. Aspects like identifying and using environmentally and socially responsible materials, minimizing carbon and particle emissions, optimizing water use, reuse and recycling, and optimizing waste generation, reuse and recycling are now being given focus during design and execution of construction projects. At the same time, the pressure for lower cost and duration in these projects is also increasing, calling for a maximization of productivity and optimization of available resources.

It can be easily inferred that, in projects involving high amount of earthworks, carbon emissions are of critical relevance. In fact, given the reliance on heavy mechanical machinery for the completion of earthwork tasks, recent large-dimension construction projects (i.e., London Olympics Stadium) have undertaken strict mitigation measures in order to minimize these emissions. Reducing the number of vehicle movements through better planning, guaranteeing that no vehicles or plant are left idle unnecessarily or setting an appropriate speed limit on haul routes are some examples of mitigation measures. While they are designed to limit emissions, these restrictions also help developers reduce fuel costs, which take up a significant percentage of earthworks costs. This hints at two practical approaches for achieving a higher level of sustainability in earthworks constructions: either indirectly, as a consequence of optimizing the usage of available mechanical resources (i.e. maximizing productivity; minimizing fuel costs); or directly, as an actual quantifiable variable which must be minimized.

In this work, the focus is given to the first approach. The adopted solution translates into an earthworks optimization system, which, leveraging on several different technologies, aims to improve the sustainability of resource allocation solutions, as an indirect consequence of minimizing both execution costs and duration. This is achieved by improving material management, optimizing the resource usage potential (i.e. mechanical equipment is used to their maximum capacity, while preventing any idle activity), and minimizing material transportation trajectories. In order to accomplish this, it is necessary to breakdown earthworks into a series of interdependent activities, in the form of production lines, based on different types of resources. The activities comprise the tasks associated with earthworks, ranging from excavation and transport to spreading and compaction, while the available resources correspond to the associated mechanical equipment necessary for each task (e.g., excavators, dumper trucks, bulldozers, rollers). Moreover, earthworks feature a series of specific characteristics, which define them as an optimization problem centered on sequential, interdependent and dynamic tasks (Gomes Correia, 2015; Parente, Cortez, & Gomes Correia, 2015; Parente, Gomes Correia, & Cortez, 2015). In fact, earthwork tasks are not only sequential, as they must be carried out in a specific order, but also interdependent, since the productivity of a task is always limited to the productivity of the tasks that precede it (i.e. lower productivity intermediate tasks will act as a productivity bottleneck, keeping the whole production line from working at its maximum productivity potential). The inherent dynamism of earthworks is related to the constant change in optimization conditions. Indeed, each time a team completes its excavation or embankment, a re-allocation of the associated equipment is required in order to keep the optimal status in the construction site. As such, bearing in mind the optimization conditions in this problem are time-evolving, the associated solution must be time-evolving as well.

This paper is organized as follows. Firstly, Section 2 comprises a description of the developed optimization system, including the used technologies and their integration. Secondly, the results associated with the application of the system to real-world data from a construction site in Portugal are shown in Section 3. Finally, conclusions are drawn in Section 4.

2 Earthwork Optimization System

Given that the purpose is to optimize earthwork production lines, a non-trivial resource allocation problem, conventional Operation Research (e.g., linear programming) and blind search methods are infeasible. As such, a potential solution is to adopt metaheuristics – modern optimization methods capable of searching large search space regions under a reasonable use of computational resources. Optimization methods such as genetic algorithms (GA) have been established as some of the most well adjusted algorithms regarding the earthworks allocation problem (Cheng, Feng, & Chen, 2005; Marzouk & Moselhi, 2002; Xu, Wang, & Xia, 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. 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).

While this may address the issue of optimizing such a complex problem, the lack of knowledge regarding optimization parameters under different work conditions, such as equipment productivity, calls for a different approach. Bearing in mind the availability of large databases, including in the earthworks area, that have been gathered in recent years by construction companies, technologies like data mining (DM) come forward as ideal tools for solving this problem. Indeed, the learning capabilities of DM algorithms can be applied to databases embodying the productivity of several equipment types when subjected to different work conditions (Cortez, Marques, & Gomes Correia, 2008; Parente, Gomes Correia, & Cortez, 2014). The extracted knowledge can then be used to estimate the productivity of the available equipment under similar work conditions. Furthermore, as previously referred, since earthwork tasks include the material hauling from excavation to embankment fronts, it also becomes imperative to analyze and optimize the possible transportation networks. In this context, the use of geographic information systems (GIS) provides an easy method to study the possible trajectories for transportation equipment in a construction site, ultimately allowing for a choice of the best paths to improve the workflow.

The result, shown in Figure 1, is a system that integrates all of these technologies, while also making use of linear programming (LP) algorithms to support resource allocation and material management. In this system, the productivity of the available mechanical equipment is estimated by the equipment module, using data mining models applied to earthworks databases, such as the *Guide des Terrassements Routiers* (GTR) (SETRA & LCPC, 2000) compaction guide. The spatial module includes the GIS data related to the optimal trajectories and transportation distances between excavation and embankment fronts in the form of an origin-destination (OD) cost matrix. The information from these modules is imported to the optimization module, which attempts to find an optimal solution for the resource allocation problem in terms of the best possible equipment fleet and its optimal distribution throughout the work area.

Bearing in mind the characteristics of the optimization problem, 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. The steps followed to determine the objective functions (total construction time and cost) are summarized in Table 1.

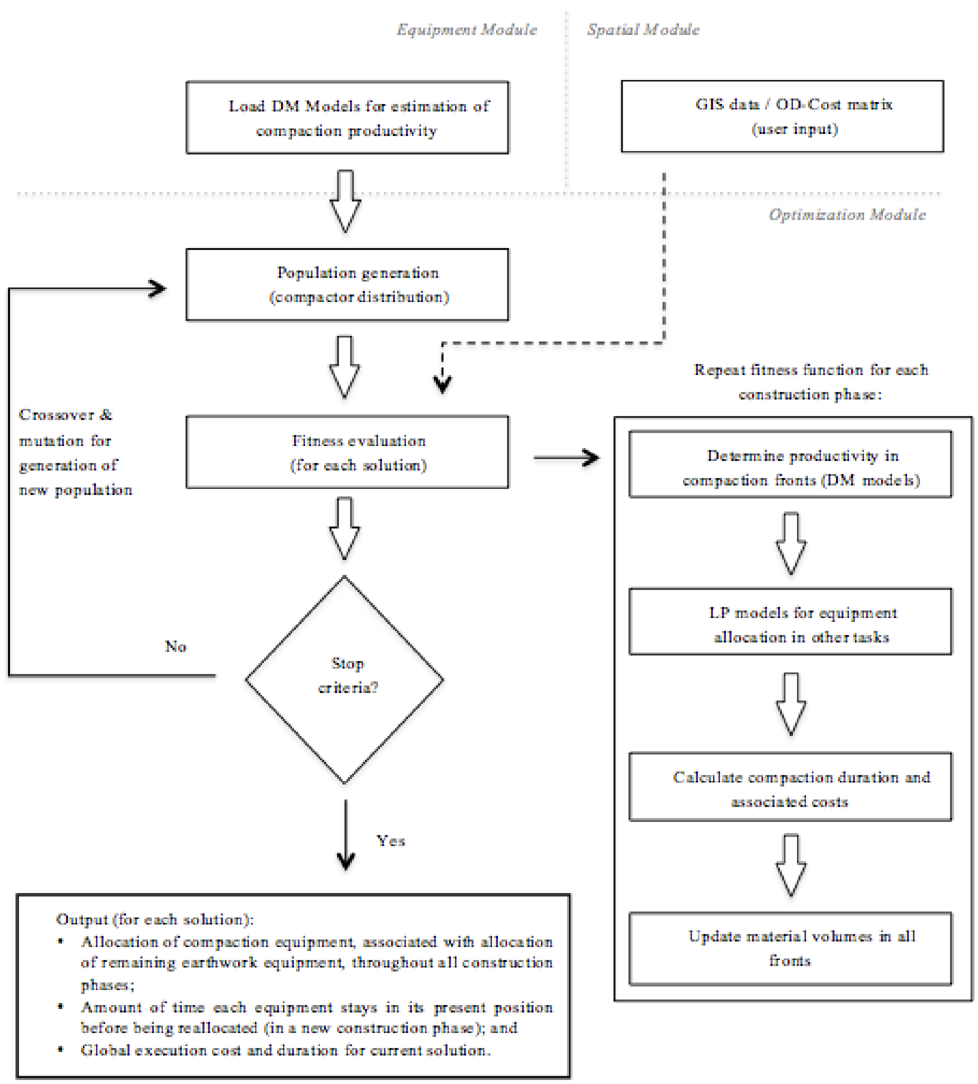


Figure 1: Integrated optimization system

As the allocation of equipment dictates the resulting construction time and cost, the usage of equipment to its full potential is paramount. In other words, the allocation of equipment takes into account the minimization of construction time and cost, but also the maximization of equipment efficiency. In turn, by using the equipment to its maximum efficiency, the subsequent solutions will inherently reduce the environmental impact of the construction (e.g. reducing carbon emissions), and increase sustainability.

In this context, and considering that earthwork construction can be interpreted as a series of production lines, global productivity will be at its highest rate when the productivity of the last task in these production lines (i.e., compaction task) is maximized. Given this premise, the allocation of equipment is firstly carried out for the compaction task, and then for each preceding task, as described in steps 1-6 of Table 1. Additionally, in order to guarantee maximum equipment efficiency, the allocation of the other tasks is performed in function of the productivity verified in embankment fronts.

Step	Description	Associated variables/factors
1	Allocation of compactors to embankment fronts	Available compactors (type and quantity); available embankment fronts
2	Determine individual productivity of the allocated compactors for each case	Compactor type; material type; compaction conditions (e.g., layer thickness, meteorological conditions)
3	Calculate total productivity in each active compaction front	Number of compactors of each front and individual productivity of each compactor
4	Allocate spreading equipment (LP model)	Total productivity in compaction task for associated embankment front; available spreaders/bulldozers (type and quantity); material type; work conditions
5	Allocate transportation equipment (LP model)	Minimum productivity in spreading and compaction tasks for associated embankment front; available trucks/dumpers (type and quantity); transportation distance; work conditions
6	Allocate excavation equipment (LP model)	Minimum productivity in transportation, spreading and compaction tasks for associated embankment front; available excavators (type and quantity), material type; work conditions
7	Calculate compaction duration in each embankment front	Productivity of production line (minimum productivity amongst all tasks in a production line); required material volumes for completing each embankment front
8	Verify fastest production line to complete its work (corresponds to the duration of the current construction phase)	Compaction duration of each production line; total volume of material required to complete each active embankment front
9	Calculate volumes of materials which have been excavated and compacted in each front during current phase	Duration of current construction phase; productivity of each production line; volume of material available/required in each active front
10	Calculate cost according to the used equipment and the duration of current construction phase	Direct and indirect costs of active equipment; duration of current construction phase
11	Verify if all embankment fronts have been completed. If not, initiate new construction phase (step 1), taking into account updated material volumes (calculated in step 9). Otherwise, output accumulated cost and duration.	Available embankment fronts (if initiating new construction phase); individual cost and duration for each construction phase (if outputting results)

Table 1: Steps for determination of total cost and duration of equipment allocation solutions

Having assembled the resulting production lines, the compaction time of each embankment front for present conditions can be determined. However, as previously referred, the earthworks optimization problem include a dynamic aspect, translating into a need to perform a new reallocation at the point in time when one of these production lines completes its work. In other words, when a team finishes its excavation or embankment work, the associated equipment becomes idle/available once again, thus changing optimization conditions. As such, a new construction phase ensues, beginning with the update of the remaining material volumes in the work fronts that have yet to be completed. These correspond to steps 7-9 in Table 1. Moreover, having the knowledge of the amount of hours each equipment has been active during the previous construction phase, it is possible to determine the time-dependent cost (e.g. fuel costs) for each active piece of equipment. By adding the result to the direct costs of active equipment (e.g. rental and manpower costs), the total cost for each piece of equipment can be calculated. The total cost for the current construction phase will correspond to the sum of the costs associated with of the active equipment (step 10 in Table 1).

Although a construction phase is considered to end as soon as a compaction front is completed, each solution evaluated by the optimization algorithm is only complete when all fronts have been compacted. As such, this process is repeated for each construction phase, calculating the associated time and cost until all fronts have been compacted (step 11 in Table 1). Ultimately, the total time and costs are determined in the end of the process by adding the values for each construction phase.

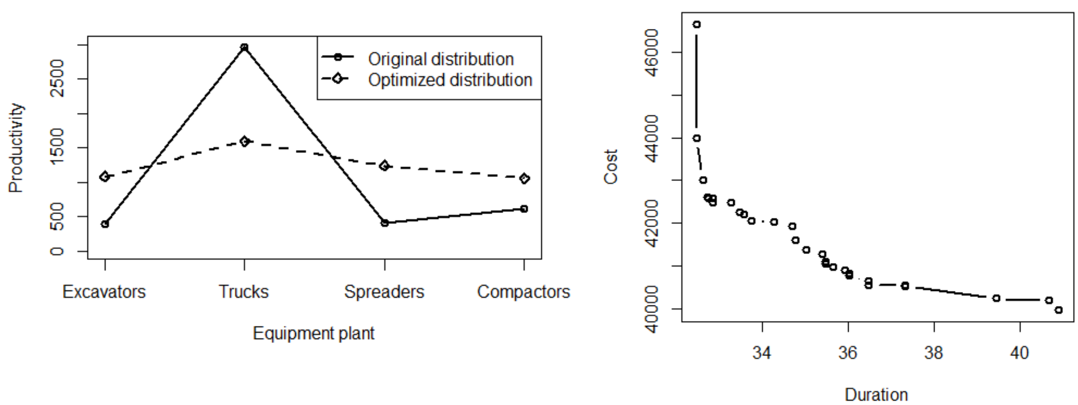
3 Results

The developed 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.

As previously referred, the purpose of the optimization system is not only to determine the solution that minimizes both cost and time for the whole earthwork construction process, but also guarantee a higher degree of sustainability. In practical terms, this includes minimal transportation trajectories, and optimal resource usage. While the former are guaranteed by the spatial module via the path-finder algorithms included in the GIS software, the latter are one of the main focuses of the optimization module. Since the productivity of the equipment allocated to a task is always conditioned by the productivity of the equipment allocated to the previous tasks, an ideal distribution solution must take into account the need to synchronize the productivity of the equipment teams that are allocated to each task. This allows for a constant flow of material from excavation to embankment fronts, thus using the allocated equipment to its full efficiency, and reducing equipment idle time. This type of aspect is very challenging to take into account using conventional design methodologies.

This is clearly depicted in Figure 2a, where it is easy to infer that the work rates in each task of the original distribution setup are not properly synchronized, as opposed to the work rates of the optimized solution. In the original equipment distribution, the productivity of the excavator team represents a bottleneck (at around 400 m3/h) for the remaining production line. This means that the transportation equipment, which has a potential productivity of nearly 3000 m3/h, is forced to wait idly for the material to be excavated before being able to transport it to embankment fronts. Consequently, this solution incurs in wastes in terms of resources (since these do not work at full efficiency), fuel and manpower (contributing to unnecessary costs), as well as an increase on unnecessary carbon emissions. As opposed to this, the production lines solutions that were output by the optimization system are as homogeneous as possible in terms of productivity. As such, a constant flow of material throughout tasks can be achieved, using the allocated resources to their full potential. As a result, besides reducing construction cost and duration, this also represents a significant increase regarding the sustainability of this solution.

By using this methodology, the system was able to achieve a high impact in both construction cost and duration for this case-study. Figure 2b illustrates the output of the system for the multi-objective (i.e., cost and duration) optimization problem in the form of a Pareto front, using the non-dominated sorting genetic algorithm-II (NSGA-II) (Deb, Pratap, Agarwal, & Meyarivan, 2002). 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 that correspond to optimal trade-offs between cost and duration, in which maximum sustainability is guaranteed according to the aforementioned methodologies. These range 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.



a.) b.)

Figure 2: a.) Comparison between equipment productivity (in m^3/h) in each task for the original equipment distribution and the optimized distribution solution; b.) Output of one run of the optimization system for the case-study (*x*-axis in hours, and *y*-axis in €)

4 Conclusions

This paper introduces an integrated intelligent earthwork optimization system, coupling AI techniques such as DM and modern optimization with GIS technology. The system is able to manage and optimize resource allocation in earthworks, minimizing execution cost and duration, while guaranteeing a higher degree of sustainability when compared to conventional design methodologies.

The results of an application of the proposed system in a case study using real-world data from a Portuguese construction site were also analyzed, showing that the system is quite competitive when compared with conventional design. In fact, for this case study, a high impact would be achieved by the implementation of this system, as results indicate a reduction of 50% to 70% in construction cost and duration when compared with the originally adopted solution (achieved via conventional manual design), assuming the feasibility of all optimization tasks. The increased sustainability of the solutions found by the optimization system derives from the optimization of resource usage potential (i.e. resources are used at maximum capacity, while preventing idle time), the improvement of material management and the minimization of transportation distances. These results bring forth the potential of the system, highlighting the importance of optimization in earthwork construction, not only in terms of cost and duration, but also as a tool that supports a more sustainable construction process.

Future work will include the exploration of an additional sustainability module. 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. This will allow for an expansion of the capabilities of the system, namely by using of the sustainability index as an actual minimization objective (similarly to cost and duration), as opposed to an indirect approach to the maximization of sustainability, as demonstrated in this paper.

Acknowledgements

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

References

Cheng, T., Feng, C., & Chen, Y. (2005). A hybrid mechanism for optimizing construction simulation models. Automation in Construction, 14(1), 85–98.

Cortez, P., Marques, R., & Gomes Correia, A. (2008). Artificial intelligence applied to compaction rules and management. In International Seminar on Interaction Soil-Rail Track for High Speed Railways. Lisbon, Portugal: Portuguese Geotechnical Society. Retrieved from http://repositorium.sdum.uminho.pt/handle/1822/11071.

Deb, K., Pratap, A., Agarwal, S., & Meyarivan, T. (2002). A fast and elitist multiobjective genetic algorithm: NSGA-II. IEEE Transactions on Evolutionary Computation, 6(2), 182–197. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=996017.

Gomes Correia, A. (2015). Geotechnical engineering for sustainable transportation infrastructure. In Proceedings of the XVI ECSMGE, Keynote Lecture (pp. 49–64). ICE Publishing.

Holland, J. H. (1975). Adaptation in Natural and Artificial Systems. Ann Arbor, Michigan: University of Michigan Press.

Marzouk, M., & Moselhi, O. (2002). Selecting Earthmoving Equipment Fleets Using Genetic Algorithms. In E. Yucesan, C.-H. Chen, J. L. Snowdon, & J. M. Charnes (Eds.), Proceedings of the 2002 Winter Simulation Conference (pp. 1789–1796). Montreal, Canada.

Parente, M., Cortez, P., & Gomes Correia, A. (2015). An evolutionary multi-objective optimization system for earthworks. Expert Systems with Applications, 42(11), 6674–6685.

Parente, M., Gomes Correia, A., & Cortez, P. (2014). Artificial Neural Networks Applied to an Earthwork Construction Database. In D. Toll, H. Zhu, A. Osman, W. Coombs, X. Li, & M. Rouainia (Eds.), Second International Conference on Information Technology in Geo-Engineering (pp. 200–205). Durham, UK: IOS Press.

Parente, M., Gomes Correia, A., & Cortez, P. (2015). Modern optimization in earthwork construction. In Proceedings of the XVI ECSMGE (pp. 343–348). ICE Publishing. doi:10.1680/ecsmge.60678.

SETRA, & LCPC. (2000). Guide des Terrassements Routiers - Réalisation des Semblais et des Couches de Forme. Paris, France: Laboratoire Central des Ponts et Chaussees.

Xu, Y., Wang, L., & Xia, G. (2011). Research on the optimization algorithm for machinery allocation of materials transportation based on evolutionary strategy. Procedia Engineering, 15, 4205–4210. doi:10.1016/j.proeng.2011.08.789.

Zhang, H. (2008). Multi-objective simulation-optimization for earthmoving operations. Automation in Construction, 18(1), 79–86. doi:10.1016/j.autcon.2008.05.002.