# Resource scheduling optimization in mass transportation problems

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## 1 Introduction

The problem addressed in this paper is a real-life earthmoving optimization problem. Our problem takes as input the optimal solution of a mass transportation problem which is one of the first operation research problems, also called *Monge-Kantorovich Problem*. This problem, initially introduced by Monge in 1781 in *Mémoire sur la théorie des déblais et des remblais* (Monge. G. 1781), has been revisited by Kantorovich in 1942 (Kantorovich L.V. 1948) and formalized by Dantzig in 1949 (Dantzig G.B. 1949). The problem consists here in scheduling a set of resources traveling between blocks located on a linear axis. This problem is introduced by "Bouygues DTP Terrassement", one of the leader of earthwork in France and is also highly active in other countries. For improving productivity and efficiency, DTP Terrassement wants to optimize the schedule of its linear construction sites (like roads, motorways, high speed rail links).

Starting from an initial altimetric profile of the construction site, earthwork consists in moving earth from several hundreds of "excavations" to dump it into "fills". The goal is to level the surface and to achieve a target profile. A block is defined by its gravity center and its list of material layers. Each material has its own properties and should be moved by some specific resources. For each layer, the exact quantity of material to move (excavation) or to collect (fill) is known. A given layer cannot be excavated until the above layer is completed. An earthmoving consists in moving a quantity $q$ of material from a source-layer with a certain quantity $q_s \geq q$ of this material, to a destination layer that expects for a quantity $q_d \geq q$ of the same material. The duration of a task may vary, depending on the amount of earth to move and on the resource used, from few days to several months. To perform these earthmovings, several types of equipments are used (or combined) to realized different kind of activities: *graders* are scratching the earth, while *loaders* are filling *trucks* and *scrapers* are moving the earth to prepare the area for the *compactors*. Resource productivity is expressed in volume moved per day. Each resource has its set of availability time windows over the horizon. Typically a resource has one or two time-windows per working day, whose length can depend on the meteorology (season). These windows take maintenance periods into account as well. Some additional restrictions prevent some resources from working on some earthmovings (complexity, skills,etc.).

The mass transportation problem computes an optimal list of earthmovings to perform on the construction site, focused on minimizing the total transportation moment. In other words, we try to minimize the product of the quantity moved by the total distance costs between source and destination blocks. All excavations should be emptied and all fills have to be fulfilled with the exact asked quantity, while using all the available quantity of these excavations. For each material, some external borrowings can be used to extract a specific quantity of this material. Similarly, to ensure the feasibility of the problem, some additional depot locations are used to store some materials, temporarily or until the end of the planning. All depot locations are not necessarily empty after the completion of a project. A linear programming approach provides an instant solution to this subproblem.

The scheduling problem takes as input the list of earthmovings resulting from the mass transportation problem. Scheduling earthmovings on a construction site consists in planning working tasks performed by resources. Each earthmoving can be handled by one or few tasks. A task is an operation moving a type of material from a block to another by using the working capacity of a authorized resource. A resource cannot work simultaneously on several earthmovings. The availability of each resource is defined through a set of time windows. The cadence of the task is defined by the association of a resource with a task (expressed in volume ($m^3$) moved per hour). Each earthmoving should be fully completed during its time windows, quite large in practice (few weeks), representing availability constraints on specific geographical areas of the construction site. Some blocks can only be reached after the erection of some constructions (like access roads or bridges) and some others could be unaccessible during few days due to other construction activities blocking the zone. The size of the problem is linear with the number of earthmovings and time windows. The summation of quantities moved by all the tasks of an earthmoving should be equal to its expected quantity. Each resource should operate only during the authorized time windows of its earthmovings. Some precedences constraints should be ensured: all earthmovings of the same block with a rank bigger than the current layer should be performed before it. Some additional precedence constraints increase the density of this PERT graph: if leveling a portion of road helps to clean the field for another work on the same portion of road, a precedence constraint is added. The objective is to minimize resources costs, divided in two parts: renting and traveling costs. The renting costs are paid for each resource, from the start of its first task to the end of its last task plus a fix cost per used resource. Traveling costs are proportional to the total distance traveled by resources between the earthmovings sources of theirs tasks.

This decomposition approach of the global problem does not guarantee the feasibility of the resulting scheduling problem, especially if precedences cycles appear. If such a case happens (rare in practice), a manual solution is to create additional depot locations to ensure the feasibility of the problem. An efficient checker of cycles run after this step helps to prevents from falling into an infeasible scheduling problem. This problem corresponds in the literature to a preemptive project scheduling with time windows, precedences, sequence dependant costs and disjonctive resources with different processing speed. Some approaches introducing earthmoving simulation are presented in (Mawdesley M.J. *et. al.* 2002, Marzouk M. and Moselhi O. 2004, Askew W.H. *et. al.* 2002, Easa S.M. 1988, Christian J. and Caldera H. 2004). Kataria S. *et. al.* (2005) present an ant colony algorithm for minimizing costs without resources schedule optimization. Section 2 presents our original local search approach for solving the scheduling optimization problem on large-scale instances. A construction site can contain up to 500 blocks, 1000 earthmovings, 50 resources and the planning horizon may reach 2 years with daily time windows.

## 2 Contribution and Results

We introduce here an original local search heuristic for solving this scheduling problem effectively and efficiency. This algorithm provides high quality solutions in a very short amount of time (less than a minute). As in precedent works in high performance local search algorithms (Estellon B. *et. al.* 2009, Benoist T. *et. al.* 2009), we strive to apply the same method of decomposition: establishment of a research strategy, design of movements adapted to the structure of our problem, and attention paid to algorithms and their implementation.

Even on large instances, the initialization algorithm computes in less than one second a first solution of the problem used as first solution for the local search. Selecting the earthmovings one by one (sorted by rank, distance, due to date and finally quantity), this greedy algorithm tries to assign missed quantity to the first available resources (sorted by first date of availability and number of tasks already assigned). There is no guaranty to obtain a solution without missed quantities using this initialization algorithm, but in practice, a first solution without missed quantities could be found for half of the instances with the greedy algorithm. After this step, the local search starts and the strategy consists in applying a first improvement descent with a random selection of the transformations (non necessarily uniform). There is no meta-heuristic with hardly tunable parameters. Transformations deal with creating, moving, shifting a whole task, a part of it or a group of tasks. Moves could be done between resources or on the same resource.

A preliminary phase in the local search algorithm is focused on minimizing the total unassigned quantities (that is to say to reach a feasible solution). Once there is no missed quantity, the algorithm switches to minimizing resource costs. Transformations on a current solution is made complex due to precedences between tasks and to multiple time windows on resources and earthmovings. A specific transformation called "k-Mirror" inverting the order of a chain of $k$ tasks has very good results for minimizing kilometers while respecting these precedences. The "engine" of the local search is built with three main procedures common to all transformations: *evaluate* (which evaluates the gain on the current objective provided by the transformation applied to the current solution), *commit* (which validates the transformation by updating the current solution and the associated data structures), *rollback* (which clears all the data structures used to evaluate the transformation). The evaluation is getting hard because any moves on a task impacts the whole planning of its resource, its earthmoving, its layer and the global objective functions values. Two crucial aspects are handled here to ensure the efficiency of the local search approach. Firstly, the precedence graph is respected, at each step, by chaining tasks in efficient data structures. If a task is moved or updated by a transformation, the current time window where it could be shifted or moved is strictly respected according to its current previous and next tasks. Secondly, we strive not to enumerate the long lists of time windows by manipulating "tasks" spanning over several time-windows and pre-computing appropriate data structures. For any resource, the ending date of an additional task can be computed dichotomously in $O(\log n)$ time, with $n$ its number of time windows. Consequently, around 120,000 transformations are evaluated each second in average in the solution space with a acceptance rate of 8 % and an improvement rate of 0.016 %. These performances ensure a high diversity of the search. The algorithm has been extensively tested on a dozen of benchmarks corresponding to real construction sites. The software integrating this heuristic is now exploited by DTP Terrassement.

Current research works are dealing with evaluating bounds. Firstly, a lower bound on the total number of kilometers traveled is computed according to the given precedences graph and distances between blocks. This problem is equivalent to the search of an optimal solution in an unidimensional T.S.P. with precedences. A second lower bound is estimated on the resource renting length according to volumes to move, cadences and time windows.

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