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Stacked Models for Earthworks Logistics: A field-tested Optimization and Simulation Workflow

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1. INTRODUCTION

Earthworks in infrastructure construction are dominated by extensive logistics operations. They have to be planned thoroughly, even in a very early phase of a project. Herein, the authors report the practical use of optimisation models and simulation to achieve an optimal allocation of transports.

Despite its commonly acknowledged usefulness in other industries, simulation of logistics systems is not yet commonplace in the construction industry. Clients usually ask for a variety of documents and calculations, ensuring a timely and highly qualitative execution of the owed work. These include construction schedules and site layouts, but hardly ever simulation models (with one of the rare exceptions being Deutsche Bahn in the project Rastatt tunnel in Germany). Occasional collaborations of academic institutions with companies in the field look promising yet still have to prove usefulness in a large scale of application (see Gschwendtner (2021) for a recent example). In general, the application of simulation appeared to be restricted to simplified cases or very special processes (Höfinger and Brunner (2016)). An interesting example of simulation is a marketing tool by an equipment vendor, allowing to select the transportation equipment suited best for the given task (Volvo Construction Equipment (2021))

Earthworks, the field of application considered herein, is typically a part of road construction, and includes all activites necessary to create a plane surface carrying the asphalt or concrete top layer of a road. Especially for green-field projects, activities are dominated by moving massive amounts of earth materials within the project area.

A logistics concept is understood here as a list of transports necessary to complete the project. A transport is defined by start and end point, transport mean, material quantity and type, and time of execution. A good or even optimal logistics concept considers re-use of materials within the site, storing and production capacities, availability and performance of machinery, road connections including temporary roads, temporal constraints, etc.

Even before actual operation, a logistics concept is used to derive schedules, estimate costs, and procure logistics ressources. Especially when working in the tender phase of a project, frequent updates to input data are made, and scenarios have to be compared. This calls for an efficient tool, allowing the creator of the concept to finish optimization cycles in the range of a few hours, which means a practically useful optimisation model has to be executed in several minutes (considering manual updates of input data, and necessary pre- and post-processing).

2. MODELS FOR THE EARTHWORKS PROCESS

With the given challenges, a workflow with three steps was designed, which can provide insights after every step. The first two steps consist of solving a linear program (LP) , while the third step is the execution of a generic simulation model, using the result of the LP model.

2.1 LP model

A detailed description of the linear programs used as first and second step is given in Dell'Amico et al. (2019). These models were first applied in 2012 for the highway project Pedemontana Lombarda in Italy (see Dell'Amico et al. (2016)) and since then used regularly for major projects tendered or executed by STRABAG AG all over the world. It has to be noted, that in pratical use cases, optimality is defined by a minimal transport effort, measured in $m^3 \cdot km$. The total flow of material is determined as a result of the first model, with the other models splitting the material flow into transports and allocating ressources to the transports, respectively. Thus, the actual optimization part is completed after the first step, allowing to stop the process of optimization, if results are undesirable or non-consistent inputs were given (infeasible model). In addition, a mathematically optimal solution is guaranteed, because LP solvers find global optima and the transport effort is not changed in the second and third step.

With demand for material (filling process, e.g. construction a road dam), supply of material (cutting process, e.g. preparing a trench) and a connection road network, in principle, a simple minimum-cost flow problem has to be solved. Adding construction related constraints (e.g. limit supply by excavating equipment), and a time dimension, the problem becomes increasingly complex. In contrast to warehouse location problems, demand and supply locations tend to be located along longitudinal axes (string of pearls), and typically a main axis dominates the topology of the network. This special structure is used to split the problem into two models. In the first phase, an optimal material flow is determined, that uniquely defines for each network edge and time step which material is transported there, where material is procured and where it is disposed. Only relations between neighbouring nodes in the network are considered, with material allowed to pass through nodes. This reduces the number of relations, and with the given structure they are in a nearly linear relation with the number of nodes instead of a quadratic one. In the second phase, transports over the network are combined in a way that the solution from the first phase is represented as transport relations, i.e. transports from a source location (e.g. a cutting location or a quarry) to a sink location (e.g. a filling location, disposal site, temporary storage) The two-phase LP model therefore creates transport relations which are connected with an arbitrary small or big quantity, which later has to be translated to single hauls by actual trucks. It provides added value, as it already solves, how demands can be fulfilled, which parts of the road network will be (over-)used, which procurement locations will be used (an important information for negotiating contracts) and what the overall haul effort, expressed in $m^3 \cdot km$ will be.

2.2 Simulation model

An important limiting factor in construction performance is the availability of haulage equipment that is often not provided by the main construction contractor but by subcontractors. Therefore, it is of importance to have knowledge about the haulage equipment at an early stage to be able to make appropriate contracts. In the LP model described above, no statements are made on individual trucks, loading and placing equipment. The intention of the simulation model is to close this information gap. The simulation model is implemented as an agent-based model in AnyLogic, using a straight-forward approach with machinery represented as agents on a network with exactly the same nodes and relations as in the LP model. The target performance of the construction equipment in combination with the distance to the optimal source/sink for each working location and assumed loading capacities and driving speeds of the haulage equipment is sufficient to trivially calculate round times and thus required truck numbers for each task. These calculations are automatically done by the simulation model.

Additionally, a schematic visualization of the process is generated as a by-product. This can be useful as a means of communication towards the client. For this standardized simulation, a 3D-representation is omitted, as 3D-data of the project is not always available, even less 3D-models for all the surrounding area relevant for logistics (quarries and dump sites typically are in radius up to 50km around a construction site).

The filling and cutting tasks are located on certain nodes of this network. The quantities for each location are stored within a so-called workstation agent. Once all workstations have reached the "done" state (i.e.: all quantities have reached 0), the simulation is finished. The actual performance of the machine is depending on the availability of a sufficient number of trucks - material can only be cut when there is a truck to load it on and only material that has already been delivered to the machine can be filled.

The present simulation model can be used on any project where an optimization with the LP model is done. The project specific need for adaption is limited to adjusting the background map and start date of the simulation model to the actual project. Unfortunately, this cannot yet be automatized due to technical reasons. Apart from that the simulation model is entirely dynamically built on data that is generated during the LP optimization process anyway. There is an analysis view within the simulation model, where real time data is visualized, e.g. number of trucks used, transport distances, processed quantities etc.

3. CONCLUSION

With our three-model approach, we are in a position to quickly evaluate major earthworks projects with respect to minimal (optimal) transport effort, usage of ressources, optimal locations for procurement etc. The workhorse of the approach is the first LP model, where the flow of material over the network is determined. Nevertheless, the following stages are necessary to create the required input for cost estimators, project technicians and procurement. The graphical capabilities of the simulation model can be used in an educational way to explain our method to teams who never worked with us (as opposed to the LP model, where only macro code can be shown). Models of this kind need comprehensive input information, available only in projects with well-designed processes, especially in the case of time-critical tender phases. The introduction of BIM is therefore a facilitator for simulation as well as many other downstream processes. With BIM becoming a standard, more and more often required by clients, together with our model, the way is pathed for a standard application of simulation in major projects in infrastructure construction.

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