BIDIRECTIONAL COUPLING OF MACROSCOPIC OPTIMIZATION AND MICROSCOPIC SIMULATION OF EARTHWORK PROCESSES

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ABSTRACT

This paper presents a bidirectional coupling concept between mathematical optimization and process simulation applied to earthwork processes in road construction projects. Considering these two techniques apart, each one has limitations in itself. On the one hand, process simulation focuses on modeling process activities and their dependencies on a very detailed, microscopic level. It helps the constructor to calculate the approximate processing time according to the resources involved. On the other hand, mathematical optimization can be used to determine cost-efficient assignments of cut and fill areas from the point of view of their capacities and distances using a graph-based approach and a linear programming technique on a macroscopic level.

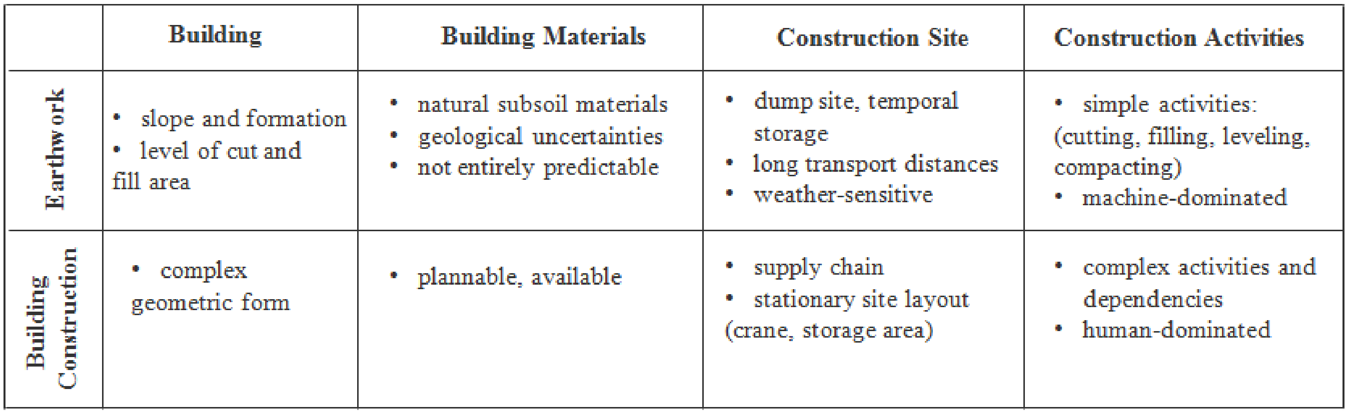
The proposed coupling concept establishes a bidirectional link between these two approaches in order to create a new framework which benefits from the advantages of both approaches and avoids the weaknesses of each individual approach. To do so, it is essential to modify the graph-based optimization model to capture information from the simulation results and to specify the common coupling parameter sharing on both sides. Test cases at the end of this paper show that the coupling framework achieves the best results in terms of reducing earthwork processing times compared with other stand-alone approaches.

Keywords: bidirectional coupling, earthwork, optimization, simulation, road construction

1. INTRODUCTION

Process simulation techniques have been intensively researched and successfully applied in the building construction industry (Stouffs et al., 1994; Zayed and Halpin, 2000; König et al., 2007; Zhang et al., 2008) and have recently been adapted to diverse civil engineering projects, such as earthwork operations (Sung-Keun and Ruessel, 2002; Dawood and Castro, 2009; Wimmer et al., 2010) and bridge construction (Wu et al., 2009), for example.

Generally speaking, the simulation technique assists the constructors in analyzing the utilization of the resources involved in the construction processes. The key to obtaining accurate simulation results is to create a simulation model which fulfills the domain-specific requirements. The differences between earthwork operations and building construction processes are depicted from different angles in Figure 1. For example, due to the geological uncertainties of subsoil layers, it is very difficult to determine the exact earthwork quantities and to choose the most suitable construction equipment in advance. Another difference lies in the geometry of the



	Building	Building Materials	Construction Site	Construction Activities
Earthwork	• slope and formation • level of cut and fill area	• natural subsoil materials • geological uncertainties • not entirely predictable	• dump site, temporal storage • long transport distances • weather-sensitive	• simple activities: (cutting, filling, leveling, compacting) • machine-dominated
Building Construction	• complex geometric form	• plannable, available	• supply chain • stationary site layout (crane, storage area)	• complex activities and dependencies • human-dominated

Figure 1: A comparison of building construction and earthwork

construction site. An earthwork construction site normally has an elongated linear shape spanning several kilometers. Traffic situations and natural obstacles surrounding the construction site need to be taken into consideration by planning earth transportation.

Optimization of earth transportation has been addressed by many researchers over the past twenty years (Easa, 1988; Jayawardana and Harris, 1990; Son et al., 2005). Here, the major objective is to minimize the total transport distances caused by earthmoving between cut and fill areas, without factoring in the earthwork processes and construction equipment. The optimal assignment of cut to fill areas can be determined exactly by solving a linear program (LP).

The simulation of earthwork processes has been studied in just a few research efforts. The main difficulties lie in the calculation of the amount of earthwork involved from uncertain subsoil data and modeling earthwork processes by taking environmental impact into account (Askew et al., 2002; Dawood and Castro, 2009). In none of the existing simulation frameworks have mathematical approaches been employed in conjunction with simulation technology to optimize the earth transportation processes.

This paper presents a novel approach which couples mathematical optimization and process simulation technology in a single framework. It benefits from the advantages of both techniques. Having introduced the simulation and optimization techniques respectively, the following sections will describe the coupling concept in detail and proceed to assessing its efficiency on the basis of test cases in the last section.

2. FORBAU SIMULATION FRAMEWORK

A 3D model-based simulation framework for earthwork processes was developed in the research cluster “ForBAU – The Virtual Construction Site” (Borrmann et al., 2009). The key features are listed below:

- Integration of diverse existing data models into a single road construction information model
- Generation of simulation source data using the computational method “*Voxelization*”
- Graph-based modeling and mathematical optimization of earthwork optimization problems
- Earthwork-specific simulation modules and application libraries

The principle architecture of the *ForBAU Simulation Framework* is illustrated in Fig. 2. It consists of two major parts: the earthwork modeling and assessment system called *ForBAU Integrator* and a discrete-event simulation system for earthwork processes.

The *ForBAU Integrator* integrates road, subsoil and terrain information in a holistic 3D data model. In order to provide simulation source data, particularly for capturing earthwork quantity data, a computational method called *Voxelization* is applied to this integrated 3D model (Ji et al., 2009). As a result, cut and fill areas are discretized into small-scale cubic elements (0.2m³) called voxels. Each voxel possesses a dedicated spatial position and subsoil property. Furthermore, individual voxels can be grouped together to form a specific aggregate structure, which can have the same size as the digger's shovel or as a dumper's load bed, for example.

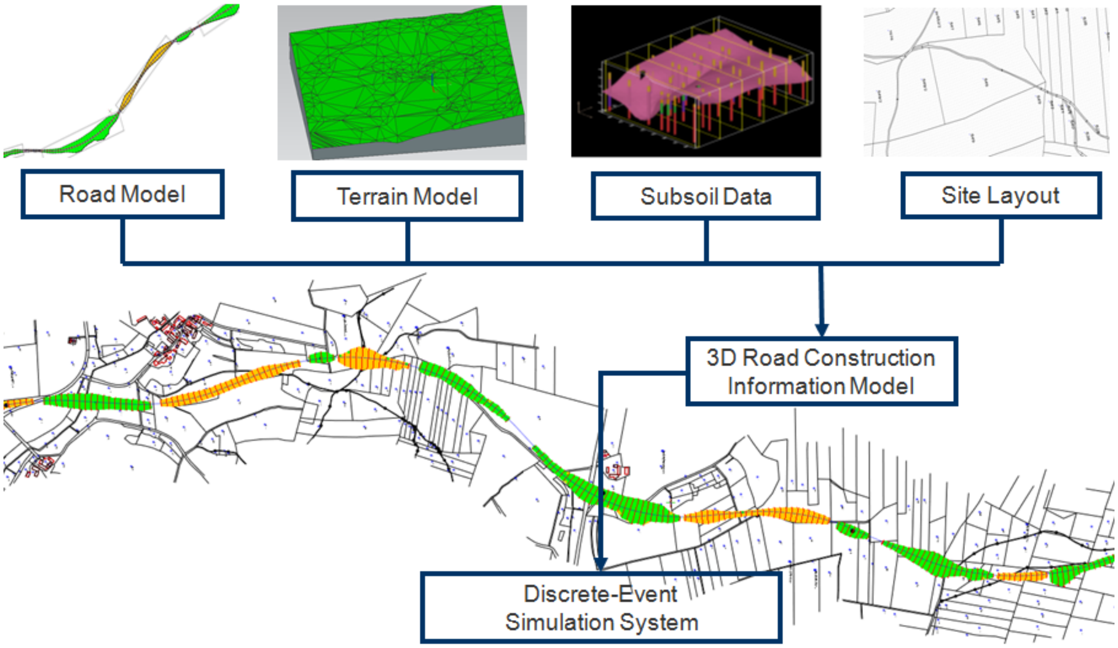


Figure 2: Overview of the *ForBAU Simulation Framework*

The resulting information provides input for the earthwork processes simulation system (Wimmer et al., 2010). The system models cost and time-critical processes hierarchically in a very detailed, realistic manner. This includes the local layout of the construction site, the required resource types and materials.

A kinematic simulation is used here to calculate the precise transportation times. This means that the acceleration capacity of the vehicle is determined in very small time-steps depending on the current speed, the properties of the vehicle and the parameters of the track. If the driving force is too small in comparison to the driving resistance, the velocity decreases over a given time step, otherwise it is increased. This offers the possibility for each vehicle to generate a velocity profile, depending on the transportation distance and the current load conditions. In addition, limiting speeds can be specified both for the vehicle, and for each section of the track to model speed limits or traffic conditions, for instance. An example of a earthwork simulation model is illustrated in Fig. 3.

3. OPTIMIZING EARTHWORK PROCESSES

Another capability of the *ForBAU Simulation Framework* is to optimize earthwork operations. In other words, it answers the question: "From which cut area how much earth has to be transported to which fill area?" The objective is to find the optimal cut-to-fill assignments in earth transportation processes which involve the shortest transport distances. This is an essential metric for evaluating the cost efficiency of earthwork transportation in current practice.

A graph-based approach has been used to solve the earthwork operation problem (Fig. 4a). We define $G = (P, E)$ to denote a bipartite graph which comprises a vertex set P and the edge set E. The set of vertices P is divided into two disjoint subsets U and V of P. The set U consists of those vertices corresponding to cut areas and, analogously, the set V represents vertices corresponding to fill areas. For each vertex $i \in P$, the parameter X_i denotes the amount of material to be removed (if $i \in U$) or deposited (if $i \in V$). We assume that the total amount to be removed equals the total amount to be deposited by introducing dump sites and borrow pits: A dump site is used to dump earth material due to material overflow. A borrow pit provides additional filling materials that have been purchased. A directed edge e_{ij} is introduced for each pair of vertices *(i,j)* where *i* is a vertex corresponding to a cut area and *j* is a vertex corresponding to a fill area. Each of these edges mirrors the possibility of sending material from a cut area to a fill area. Additionally, each edge e_{ij} has an associated cost c_{ij} which represents the cost of transporting one mass unit of material from *i* to *j*.

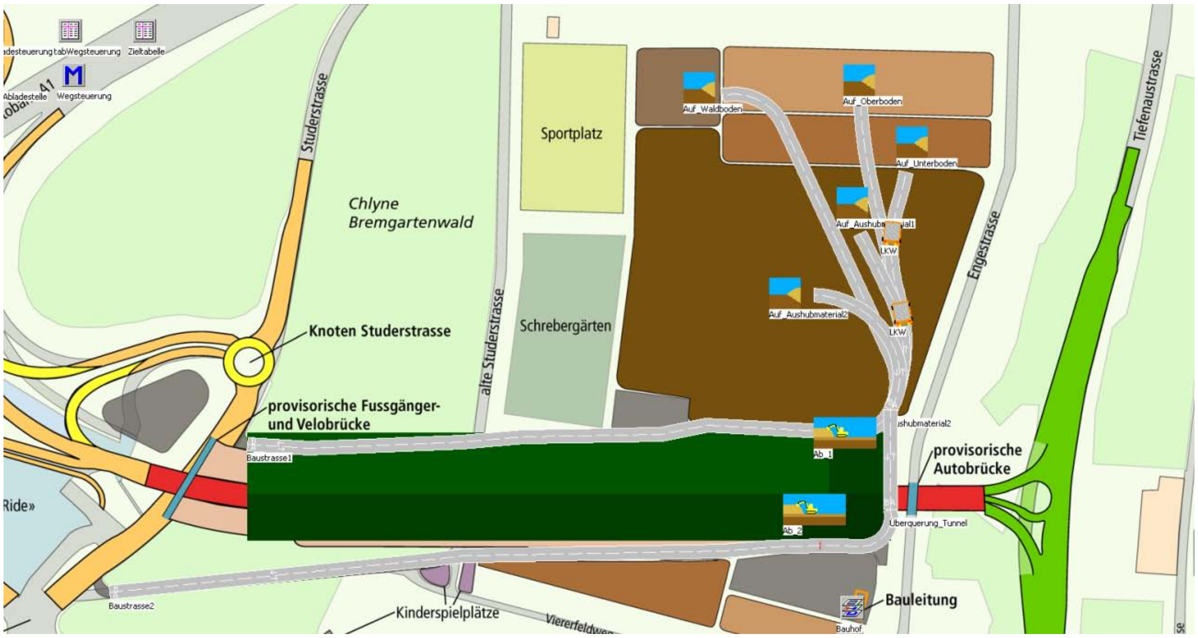


Figure 3: Example of a simulation model of earthwork processes

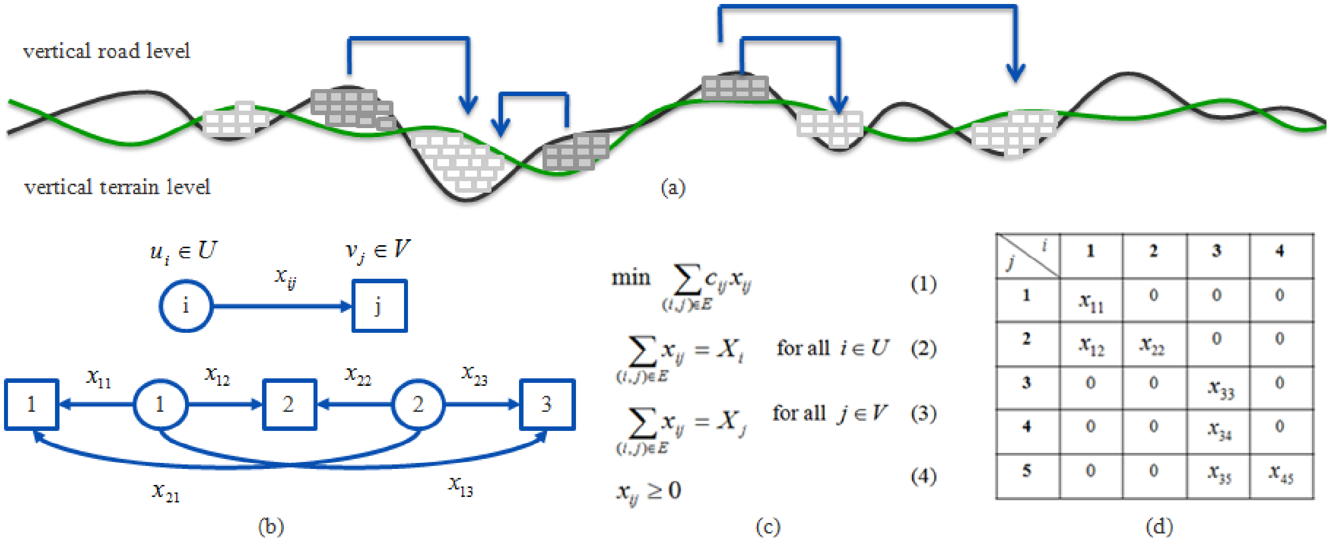
A simple example is shown in Fig. 4b. The graph-based representation can easily be translated into a linear program. A decision variable x_{ij} is assigned to each of the directed edges in the set *E*. It denotes the quantities of earth to be hauled from cut *i* to fill *j* following the edge direction (Fig. 4c). The transportation cost along each edge *(i,j)* has to be non-negative. The objective function (1) models the minimization of the total transportation cost. Due to the fact that in the real world only positive material flows make sense, the decision variables x_{ij} are restricted to be non-negative (constraint (4)). Constraint (2) implies that the total quantity of material to be hauled from some cut area i to all fill areas equals the total quantity of material X_i provided by the *i*-th cut. Constraint (3) is similar to (2) for the requirements in *j*. This formulation is a simplified *minimal cost flow problem* and can be satisfactorily solved using network flow algorithms (Ahuja, 1993). Solving the optimization model above furnishes the amount of earth x_{ij} to be moved from a cut area *i* to a fill area *j*, while keeping the overall transportation cost to a minimum (Fig. 4d).

4. BIDIRECTIONAL COUPLING

As mentioned above, the mathematical optimization of cut-to-fill assignments can minimize the total transport distances and accordingly reduce transport costs. Resource involvement and process dependencies are not considered in the graph-based optimization model, however. At the same time, simulation techniques can be applied to model earthwork processes taking the available resources and predefined transport assignments into account.

The proposed coupling framework establishes a bidirectional link between these two parts to complement each other. In the coupled system, cut-to-fill operations proposed by mathematical optimization are imported into the simulation system. The simulation of earth transportation processes is then performed on the basis of these input data and resource dependencies. As a result, earthwork durations between cut and fill areas can be determined and imported back to the mathematical optimization. Transport durations can be used instead of transport distance in the optimization model. It is subsequently possible to optimize the total earth transport duration in an iterative manner.

To realize this, two major steps have to be performed: first of all, the graph-based optimization model needs to be modified to capture information from the simulation results, after which the common coupling parameter sharing both sides has to be specified.



$$\min \sum_{(i,j)\in E} c_{ij} x_{ij} \quad (1)$$

$$\sum_{(i,j)\in E} x_{ij} = X_i \quad \text{for all } i \in U \quad (2)$$

$$\sum_{(i,j)\in E} x_{ij} = X_j \quad \text{for all } j \in V \quad (3)$$

$$x_{ij} \geq 0 \quad (4)$$

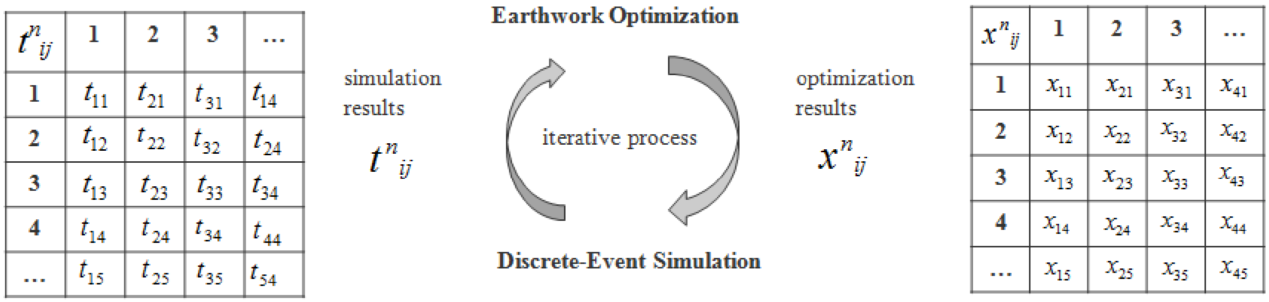
j \ i	1	2	3	4
1	x_{11}	0	0	0
2	x_{12}	x_{22}	0	0
3	0	0	x_{33}	0
4	0	0	x_{34}	0
5	0	0	x_{35}	x_{45}

Figure 4: (a) Illustration of cut-to-fill assignments problem; (b) corresponding bipartite graph model; (c) Formulation as linear program; (d) optimal cut-to-fill assignments in matrix form

The graph model G is extended by an additional edge weight t_{ij} which denotes the transportation time between the cut and fill operations. As mentioned above, the key issue behind this concept is to take advantage of bilateral interaction between optimization and simulation, which means that the transportation time t_{ij} can be obtained from the process simulation results. These durations t_{ij} are then used as edge weights instead of pure distances in the graph model G. The coupling approach is designed as an iterative algorithm consisting of the following essential steps:

- import optimized cut-to-fill assignments into the simulation system
- run earthwork simulation according to the optimization results
- re-import simulation results into the optimization system

The formal specification of the coupling approach is depicted in Fig. 6. The first coupling parameter x_{ij}^{n} contains all optimal cut-to-fill assignments in the earthwork processes in the *n*-th iteration. Indices *i* and *j* denote the identifier of cut and fill areas. At the beginning of the iteration, due to the fact that there are no available simulation results which can be used as input for the optimization, x_{ij}^{0} is initialized with the efficient transport distance between cut and fill areas. The opposite coupling parameter is the earthwork transport duration matrix t_{ij}^{n} which indicates the actual working time required to finish the earthwork process resulting from cut-to-fill assignments identified by the pair of indices *(i,j)* in the *n*-th iteration. As mentioned above, this time factor is obtained as a result of microscopic process simulation under consideration of all process resources and activities involved. In particular, it is evident that excavating and loading as well as unloading and leveling processes have a significant influence on the total duration of the earthworks. The earthwork duration matrix will subsequently replace the initialized transport distance matrix and serve as edge weights in the bipartite Graph *G*. Where there is no assignment between a cut and a fill area, the earthwork duration time will be estimated on the basis of the average processing time.



t^n_{ij}	1	2	3	…
1	t_{11}	t_{21}	t_{31}	t_{14}
2	t_{12}	t_{22}	t_{32}	t_{24}
3	t_{13}	t_{23}	t_{33}	t_{34}
4	t_{14}	t_{24}	t_{34}	t_{44}
…	t_{15}	t_{25}	t_{35}	t_{54}

x^n_{ij}	1	2	3	…
1	x_{11}	x_{21}	x_{31}	x_{41}
2	x_{12}	x_{22}	x_{32}	x_{42}
3	x_{13}	x_{23}	x_{33}	x_{43}
4	x_{14}	x_{24}	x_{34}	x_{44}
…	x_{15}	x_{25}	x_{35}	x_{45}

Figure 5: Specification of couplings parameter in the iterative process

The following iterations follow the same principle. The iteration terminates when the earthwork efficiency matrix converges to a stable value or the predefined number of iteration steps is reached. This serves to optimize the earth transportation process.

5. APPLICATION AND TEST RESULTS

The coupling concept presented in this paper was implemented in the *ForBAU Simulation Framework* and applied by way of a prototype in a large German federal road construction project. The earthwork construction site has a length of 12 kilometers and is divided into 16 cut areas and 17 fill areas.

As soon as the holistic 3D construction information model has been successfully generated (see background of Fig. 2), the earthwork volume is calculated using the voxelization algorithm and the earth transport network is made available for process simulation. The earthwork simulation was set up with one excavator and three dumpers. Different scenarios have been created and investigated in order to assess the coupling concept.

As shown in Fig. 6, the first simulation experiment is based on cut-to-fill assignments which are carried out without any optimization. Obviously, for such a big earthwork construction side, the randomly chosen cut-to-fill operations caused the longest simulation time.

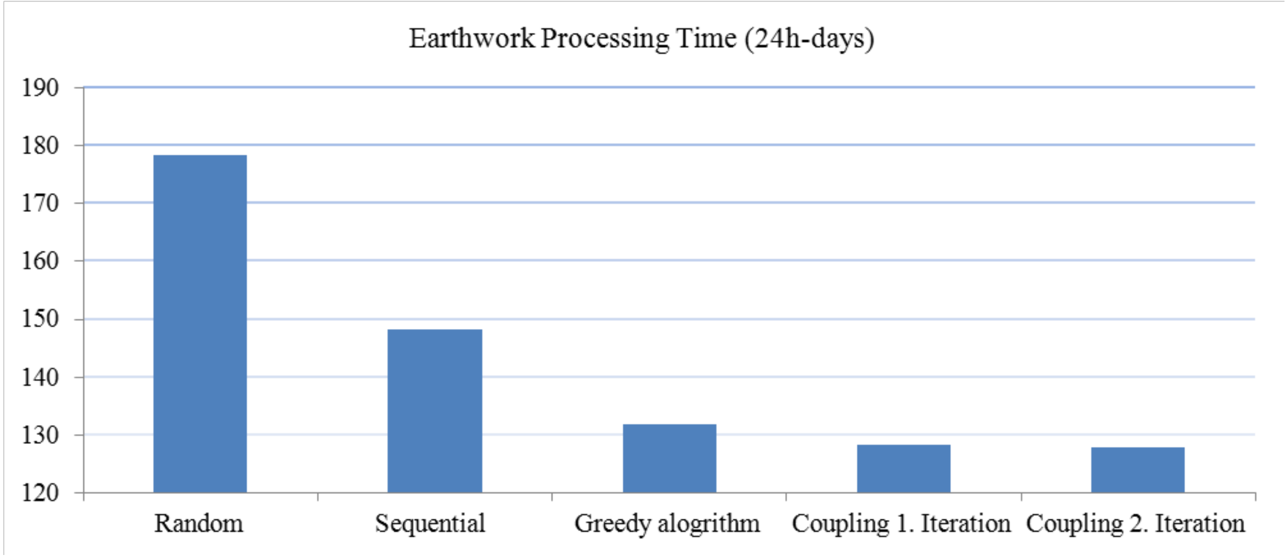


Figure 6: Comparison of earthwork processing times using different approaches

The second experiment follows the principle “as simple as possible”. The cut-to-fill assignments are allocated in sequence by the geographical locations of the cut and fills areas alongside the earthworks. The cut areas will be excavated one by one and the earth materials transported to the fill areas according to their geographical location. It may seem surprising that more than 30 days can be saved by using this simple assignment strategy.

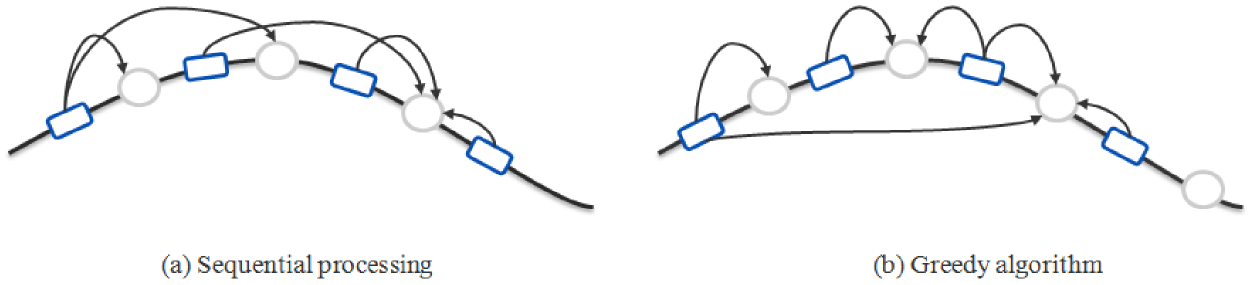

(a) Sequential processing (b) Greedy algorithm

Figure 7: Comparison of earthwork processing times using different approaches

In the third experiment, the *Greedy algorithm* (Michalewicz and Fogel, 2004), a heuristic approach, has been applied to find the next nearest fill areas for each cut area. Figure 7 shows the difference between these two methods. The *Greedy algorithm* assigns the optimal fill area for the filling operation concerned in terms of transportation distance or duration from a local point of view. In the case of a curved alignment, the *Greedy*-based cut-to-fill-assignments will differ significantly from the sequential approach. 16 additional working days can be saved using the heuristic approach.

The last experiment was used to test the coupling approach. In the first iteration, only 128 days are required for completing the earthwork processes, based on the same construction resource conditions. Compared with the sequential approach, more than 20 working days can be saved and, even in comparison with the heuristic approach, it is possible to reduce the operations by 4 additional days. In the second iteration, the working time is reduced by just 3 hours. This means that the coupling algorithm converged in only a few iterations.

The first test results confirmed the feasibility of the proposed coupling concept. It is important to note that the implemented simulation model does not contain all types of measurement data from the construction site, for example, the workers' break time, maintenance stops for the construction equipment, traffic conditions around the earthwork construction site and the impact of weather on the earth transportation operations. Thus, this simulation time does not state the construction time in an absolutely realistic way. More test cases with extra configuration parameters will be carried out in future research work.

6. CONCLUSIONS AND OUTLOOK

This paper has presented a concept for the bidirectional coupling of macroscopic optimization and microscopic simulation of earthwork processes. The objective of this concept is to optimize earthwork efficiency through the iterative interaction between mathematical optimization and process simulation. It avoids setting up a large-scale, complex optimization system. The mathematical optimization produces exact results while the process simulation system provides a detailed modeling of non-linear activities in earthwork processes.

Test cases using data from real-world construction projects verify the proposed coupling concept. It is possible to reduce the duration of the earthworks over a number of iterations. The further treatise will be dedicated to carrying out additional scenarios based on extended parameter configurations.

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