Coupling Microscopic Simulation and Macroscopic Optimization to Improve Earthwork Construction Processes

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Abstract. This paper presents a novel method for improving earthwork construction processes by coupling microscopic process simulation and macroscopic optimization approaches. It is designed as an iterative process where simulation and optimization procedures alternate with one another and exchange data with each other. The optimization module determines the optimal allocation of earthwork masses from cut to fill areas, in the first cycle with respect to distances and later in terms of haulage time. The generated output is used in the simulation module for routing the transport vehicles accordingly. Subsequently, the process time is determined in the simulation procedure by including diverse microscopic conditions. The resulting process time on each route is then used in the next optimization step as input for optimizing the earthwork allocations. The coupling cycle is repeated iteratively until the total earthwork process time converges. Initial tests based on input data of real high-way construction projects record a significant reduction in the total earthwork process time.

1 Introduction

The motivation for applying simulation and optimization approaches to the construction industry is to assist construction engineers in enhancing the productivity on the construction site. By using process simulation tools, construction engineers are able to identify dependencies between construction processes and analyze the use of resources involved. Different simulation scenarios can be easily created, for example, by varying the number and type of construction devices or by changing the order of individual process steps. Generally speaking, process simulation techniques are microscopic approaches. Their counterparts, macroscopic optimization approaches, are often used to optimize the sequences of process steps in order to enhance the overall system efficiency and accordingly reduce the total process time.

This paper focuses on minimizing the total earthwork duration by using a new method which takes advantage of process simulation and optimization approaches. It aims at reducing the total earthwork time and enhancing haulage efficiency of subsoil materials on the construction side. The principle of earthwork processes considered here consists of three basic earthwork operations *excavation*, *transportation* and *compaction*. These operations and the construction equipments involved are interrelated in the following way: soil materials are excavated from cut areas using excavators (usually diggers) and loaded on to transport vehicles (such as dumpers). Depending on the geological reusability of the materials concerned, the haulage trucks carry them from the cut areas to either the fill areas or to landfill sites respectively. On arrival at the fill areas, the materials are compacted using compacting devices. If there is insufficient soil available, additional materials need to be purchased and transported to the earthwork construction site.

The paper is organized as follows: After introducing microscopic simulation and macroscopic optimization approaches in Section 2, Section 3 describes the developed mechanism for coupling both approaches including a detailed explanation of the iterative procedure. Section 4 presents a test case in which the coupling approach has been applied. Section 5 concludes the paper and discusses future research work.

2 Microscopic and Macroscopic Approaches

2.1. Microscopic Simulation of Earthwork Processes

The state-of-the-art in simulating earthwork processes focuses on modeling earthwork operations and their interdependencies in detail (Martinez, 1998; Askew et al., 2002; Sung-Keun and Ruessel, 2002; Borrmann et al., 2009; Dawood and Castro, 2009). The underlying simulation methods are mainly based on the discrete-event approach, which was originally developed for factory planning in the manufacturing industry, or on Petri-net models (Chahrour, 2006; Luo et al., 2008; Cheng et al., 2011). Both of these methods are variations on the microscopic approach, because the interdependencies between individual process steps and the interaction between simulation components are described on a microscopic level.

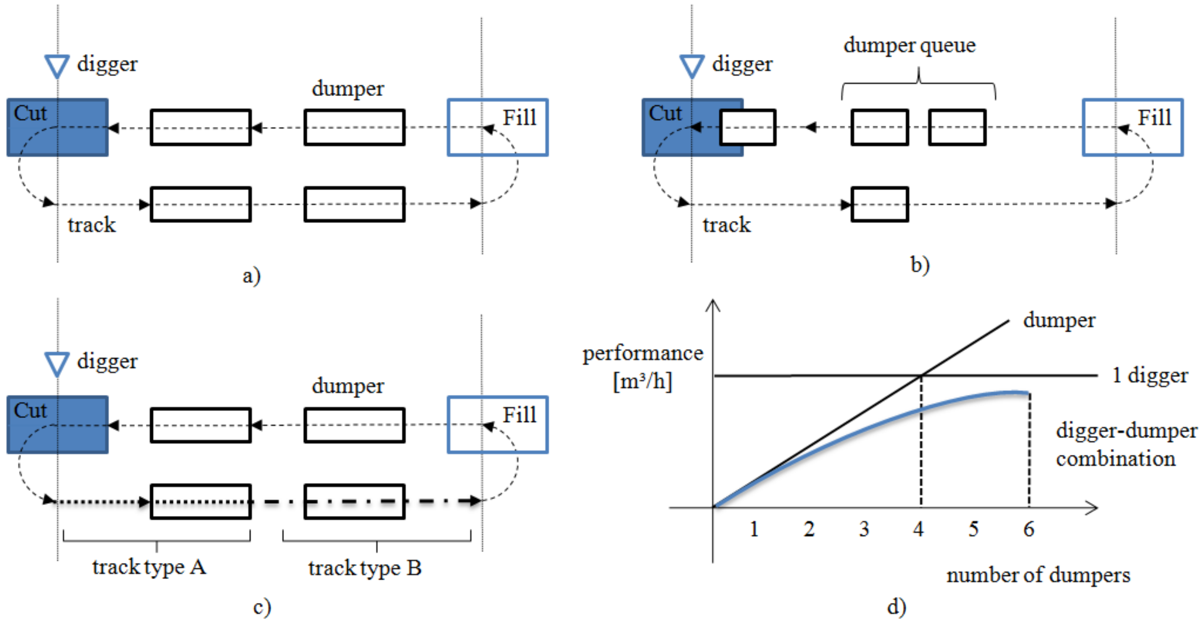


Figure 1: Detailed modeling of earthwork processes under consideration of microscopic conditions; a) ideal process b) waiting queue c) properties of tracks d) non-linear working performance in earthwork processes

Figure 1 shows a model for simulating parts of the earthwork process. The interaction between various types of earthwork equipment (digger and dumper), the earthwork operations *excavation* and *transportation,* as well as the transport routes (tracks) are the basic components of the simulation model (Figure 1a). Using these components, the simulation engine can run the earthwork process virtually and not only determine the overall process time but also the performance of individual machines by including different microscopic conditions. One of these is illustrated in Figure 1b, where a slowly performing digger forces the dumpers to queue until the digger is available. The resulting waiting time naturally has to be taken into account when determining the total earthwork duration. The process becomes even more complex when compacting devices are involved. Another type of microscopic effects occurs when the individual tracks provide different transport conditions that have a significant impact on the performance of the haulage vehicles (Figure 1c). There are many other microscopic effects that need to be considered. If we take them all into account, the analytical determination of the overall process time becomes so complex that a simulation technique is required (Wimmer et al., 2010). As the simple digger-dumper process shows, for example, the resulting working performance is not linearly dependent on the number of diggers and dumpers (Figure 1d), so the process time cannot be directly calculated using theoretical performance factors of the construction apparatus. Instead, microscopic simulation approaches are employed to make precise statements about the process time and utilization of resources involved.

A very time-consuming aspect of microscopic simulation is specifying the resource quantities and defining the process dependencies. Determining the amount of earth to be transported between the individual cut and fill areas is a particularly important part of earthwork simulation. There is enormous potential for applying optimization approaches in this sphere. Apart from a few exceptions (König and Beißert, 2009; Hamm et al., 2011), optimization methods are not a primary part of microscopic simulation approaches. Instead, the user is required to systematically vary the input parameters to create a wide range of simulation scenarios in order to find the optimal result, or at least a good one. This is mainly due to the fact that a simulation model does not describe the entire process system in an analytically closed manner which is required to apply non-heuristic optimization techniques.

2.2. Macroscopic Optimization of Earthwork Allocation

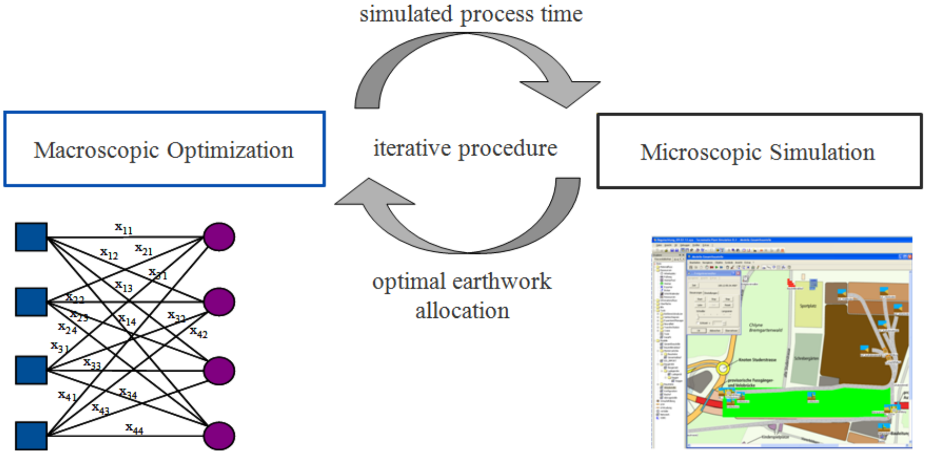
In contrast to microscopic approaches, mathematical optimization methods at the macroscopic level have been applied for a long time (Easa, 1988; Jayawardana and Harris, 1990; Marzouk and Moselhi, 2004; Son et al., 2005; Ji et al., 2010a). These macroscopic approaches ensure optimal earthwork allocation between cut and fill areas. However, only macroscopic conditions, such as the "capacity" of cut and fill areas and the transport distances, are taken into account. The result is an assignment of earthwork masses to each cut-to-fill pair designed to minimize the total transport distance. None of the microscopic effects mentioned in Section 2.1 are taken into consideration in the optimization, so it is not possible to optimize the total earthwork process time.

This paper accordingly introduces a new method of optimizing the overall earthwork process time by combining the advantages of macroscopic and microscopic approaches. The coupling of microscopic simulations with macroscopic optimizations is a general powerful methodology which we have already successfully applied to pedestrian dynamics (Kneidl et al. 2010) and will do so for other dynamic processes in the future.

3 Iterative Coupling of Microscopic and Macroscopic Approaches

3.1 Principle

The new method is based on coupling microscopic simulation and macroscopic optimization approaches. It is designed as an iterative procedure, where simulation and optimization module alternately take control in the iteration steps and exchange data with each other. The iteration stops as soon as the coupling data converges. This makes it possible to determine the optimal earthwork allocation for minimizing the overall process time. The basic idea of the coupling concept is depicted in



Figure

Figure 2 2.

First, the optimal assignment of cut to fill areas is determined using macroscopic optimization on the basis of *distances* between cut and fill areas. The optimization results are imported into the microscopic simulation and used as an input parameter for routing the haulage trucks travelling between the cut and fill areas. In the next step, the simulation module determines the earthwork process time for each allocation by taking microscopic conditions into account, and passes the simulation results back to the optimization module. After the first iteration, the optimization module uses the earthwork *process time* as its input and determines the optimal earthwork allocation accordingly. The iteration process is repeated until the total earthwork time converges.

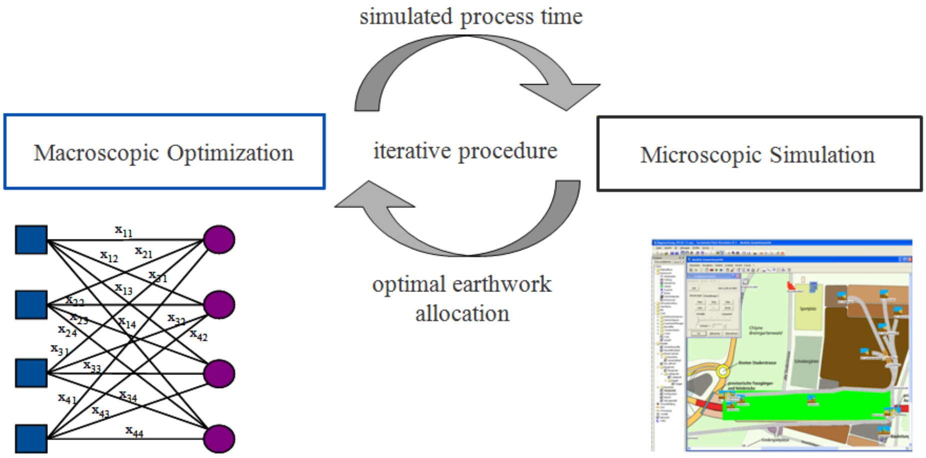


Figure 2: Principle of the iterative method coupling microscopic simulation and macroscopic optimization

3.2 Initial Optimization

As mentioned before, the first optimization procedure is carried out on the basis of the pure transport distances between cut and fill areas. A bipartite graph *G* is used here to model the earthwork allocation problem (Figure 3a and 3b). A directed edge (*i, j*) in *G* denotes the flow of earth excavated in *i* to fill *j*. The edge weights are assigned with the haulage distance from *i* to *j*. Accordingly, solving the resulting linear program (Easa, 1988; Ahuja, 1993) provides the optimal allocation of earthwork between cut and fill areas amounting to x_{ij}. Figure 3c shows such a coupling pattern in the form of a matrix. The reader should note that in the initial optimization step the transport distance between cut and fill areas is subject to optimization. Under the assumption, the transport distance is the most influential cost factor.

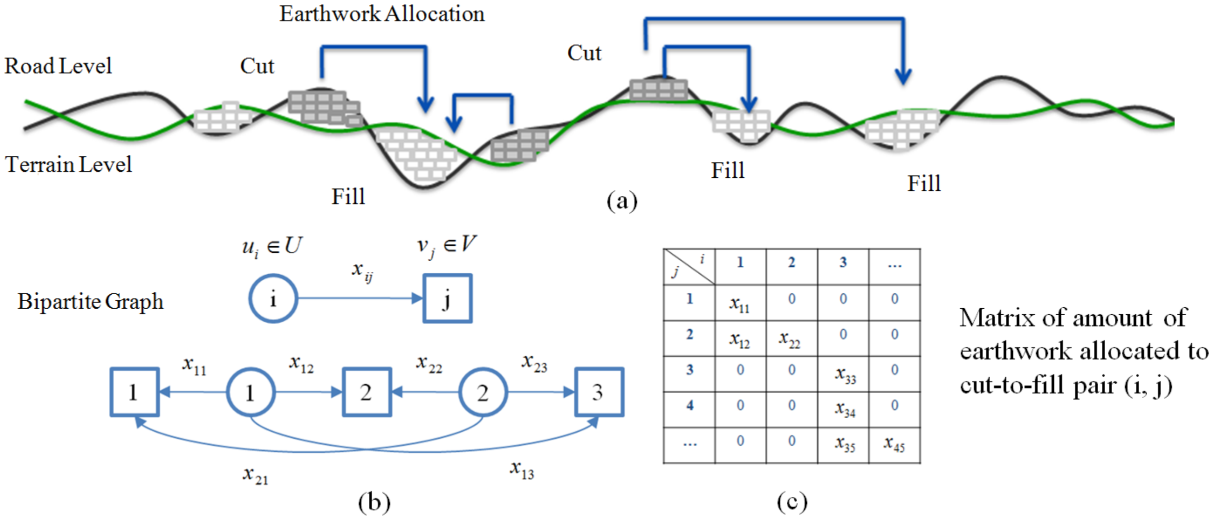


Figure 3: Schematic representation of modeling the earthwork allocation problem with a bipartite graph; the optimal cut-to-fill allocations can be represented using a transport matrix

In the next iteration step, the earthwork process time of each individual route (graph edge) is used as an input parameter for the optimization module. The edge weights of the graph G are set accordingly. Now, the optimization procedure outputs the earthwork allocation which represents the minimal overall earthwork duration.

In most cases, there will be cut-to-fill pairs to which a zero value of earth haulage is assigned, meaning that there are not used in the simulation module. Accordingly the process time cannot be determined, i.e. the corresponding edges will not possess a weight when the network is imported back into the optimization module. The optimization process will disregard these edges, thus decreasing the solution space at each iteration. To prevent this happening, more suitable edge weights have to be chosen.

The goal is to find a measure that makes it possible to estimate the edge weight for those edges which have not been used in the simulation. This can be done by using *Specific Material Flow* F_i as an edge weight. If edge *i* has been used in the simulation, then

$$F_i = m_i / t_i \qquad [m^3/h]$$

where m_i is the amount of earth transported and t_i is the simulated earthwork process time. Comprised with the initial optimization step, the transport duration between cut and fill areas is subject to optimization. The inverse of F_i that represents the transport resistance is considered as major factor affecting the transport duration.

If the edge has not been used, the calculation of the *Specific Material Flow* is more complicated. First, the *Normalized Material Flow* F_i^N must be computed. It represents the objective quality of a certain route (edge) by eliminating the impact of the transport distance on the transportation time. F_i^N is formulated as

$$F_i^N = \frac{m_i}{t_i} \cdot d_i = \frac{m_i}{d_i/v_i} \cdot d_i = m_i \cdot v_i \qquad [m^3 km/h]$$

where m_i is the amount of earth transported, t_i is the simulated earthwork process time, d_i is the transport distance and v_i is the speed of material flow. As the equation shows, the influence of transport distance and the transport time are eliminated by the speed of material flow in F_i^N.

In the next step, the *Average Normalized Material Flow* $\hat{F}^N$ is defined as

$$\widehat{F^N} = (\sum_{i=1}^{n} F_i^N)/n \qquad [m^3 km/h]$$

where n is the number of weighted edges.

Finally, the *Specific Material Flow* for those edges which have not been used in the simulation can be determined by

$$F_i = \widehat{F^N}/d_i \qquad [m^3/h]$$

Using the *Specific Material Flow* instead of earthwork process time is a further step towards improving the existing coupling approach. It is a suitable optimization criterion because a high material flow indicates high transport efficiency in the earthwork process and low transport resistance accordingly. The total time of the earthwork operations will be reduced by maximizing the total material flows. Moreover, the bipartite graph G stays fully connected during the entire iteration procedure, so the solution space of the optimization problem is not reduced. The optimization module will maximize the material flows and provide the resulting optimal earthwork allocation to the next simulation procedure (Figure 4).

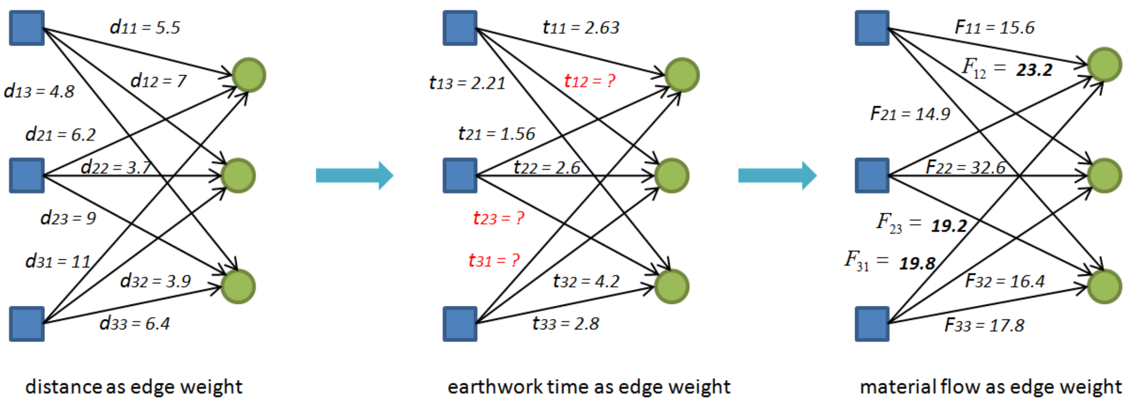


Figure 4: Converting the earthwork process time in material flow for each cut-to-fill pair

3.4 Further Iterations

In the subsequent iterations, the simulation module determines the earthwork process time according to the optimal earthwork allocation given by the optimization module. The simulated earthwork process time is then converted into normalized material flows. The optimization module maximizes the material flows and provides the corresponding new earthwork allocation for the simulation module.

In a single iteration, the new earthwork allocation changes the overall microscopic effects in the simulation module, which has a significant impact on the earthwork duration. Accordingly, the newly determined earthwork duration ultimately makes a further adjustment to the earthwork allocation required. The coupling procedure therefore needs to be repeated until the normalized material flow has converged.

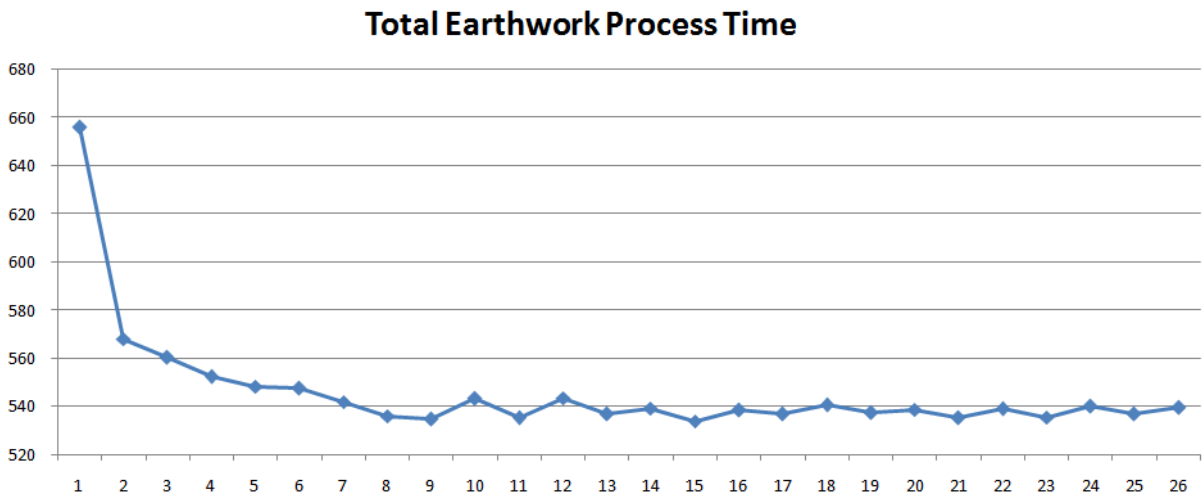


Figure 5: Changes of total earthwork process time [h] (vertical direction) during 26 iteration steps (horizontal direction)

4 Test Case

The coupling method is tested on the basis of input data from an actual highway construction project in Germany covering 50 kilometers and consisting of 33 cut areas and 32 fill areas. The total earthwork amounts to 440,324 m³. By using the distance-based optimization method, the total earthwork is completed within 656 working hours employing one digger and five dumpers. The total earthwork process time and the total material flows during the iteration steps are depicted in Figure 5 and Figure 6. Both a significant reduction of the total earthwork process time and a clear increase of the total material flows in the earthwork processes can be identified. In comparison with the pure distance-based optimization, the coupling approach improves the earthwork transport efficiency by 18.4% in this test case. The total earthwork process time converges very quickly in a few iteration steps.

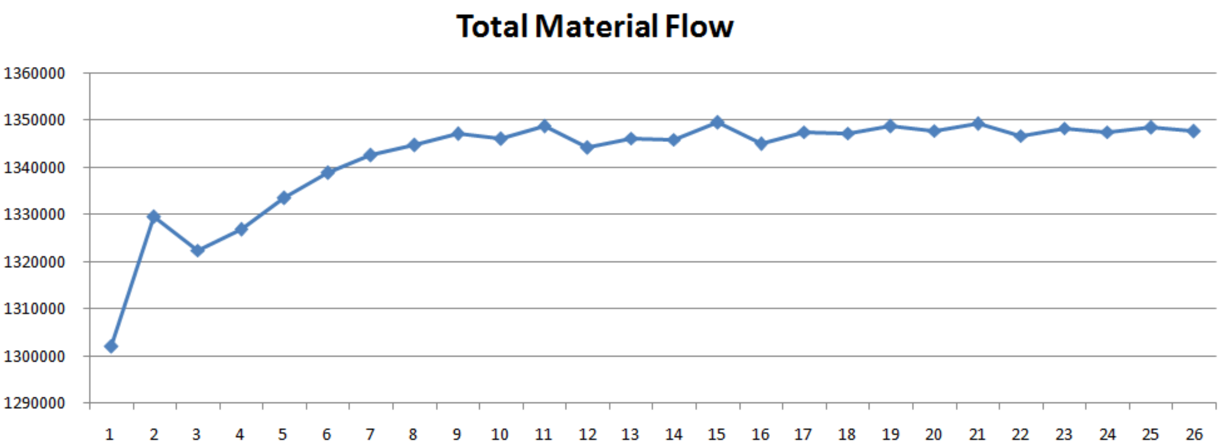


Figure 6: Changes of total material flows [m³/h] (vertical direction) during 26 iteration steps (horizontal direction)

5 Conclusion and Outlook

The paper has presented a method for optimizing the duration of earthwork processes which couples microscopic simulation methods and macroscopic optimization approaches. It allows to minimize the total earthwork duration using a non-heuristic optimization technique while taking into account microscopic non-linear effects.

This is realized by an iterative process in which simulation and optimization alternate and exchange data with one another. The optimization module determines the optimal allocation of earthwork between cut and fill areas which will be used in the simulation module as a basis for routing the subsoil transport equipment. The earthwork process time for each route can be determined taking the microscopic conditions into consideration. The next step is to use the earthwork process time to calculate the material flows in the subsequent optimization procedures. The process is repeated iteratively until convergence is reached.

Initial tests of the coupling approach, based on input data from a real high-way construction project in Germany, have shown a significant reduction in the total earthwork process time and a clear increase of haulage efficiency in the earthwork processes. The total earthwork time soon converges after just a few iterations. Ongoing research will address a comprehensive validation of the method introduced in this paper in collaboration with various construction companies.

The presented approach of coupling macroscopic optimization with microscopic simulation is a powerful general methodology and applicable to a broad range of process types. Future publications will include more application scenarios where the coupling mechanism can be applied beneficially.

References

Ahuja, R., Magnati T. L., Orlin, J. B. (1993) Network Flows. Prentice Hall, Inc.

Askew, W.H., Al-Jibouri, S. H., Mawdesley, M. J., Patterson, D. E. (2002) Planning Linear Construction Projects - Automated Method for the Generation of Earthwork Activities. Automation in Construction, vol. 11, issue 6, pg. 643-653.

Borrmann, A., Ji, Y., Wu, I.-C., Obergrießer, M., Rank, E., Klaubert, C., Günthner, W. (2009) ForBAU - The Virtual Construction Site Project. Proc. of the 26th CIB-W78 Conference on Managing IT in Construction, Istanbul, Turkey.

Cheng, F. F., Wang, Y. W., Ling, X. Z., Bai, Y. (2011) A Petri Net Simulation Model for Virtual Construction of Earthmoving Operations. Automation in Construction, vol. 20, issue 2, pg. 181-188.

Dawood, N., Castro, S. (2009) Automating Road Construction Planning with a Specific-domain Simulation System. Journal of Information Technology in Construction, vol. 14, pg. 556–573.

Easa, M. (1988) Earthwork Allocations with Linear Unit Costs. Journal of Construction Engineering and Management, vol. 114, issue 4, pg. 641-655.

Hamm, M., Szczesny, K., Nguyen, V. V., König, M. (2011): Optimization of Construction Schedules with Discrete-Event Simulation using an Optimization Framework. Proc. of the 2011 ASCE International Workshop on Computing in Civil Engineering, Miami, FL, USA.

Jayawardana, A. K. W., Harris, F. C. (1990) Further Development of Integer Programming in Earthwork Optimization. Journal of Construction Engineering and Management, vol. 116, issue 1, pg. 18-34.

Ji, Y., Seipp F., Borrmann A., Ruzika, S., Rank, E. (2010a) Mathematical Modeling of Earthwork Optimization Problems. Proc. of the International Conference on Computing in Civil and Building Engineering (ICCCBE), Nottingham, UK.

Ji, Y., Borrmann, A., Wimmer, J., Günthner, W. (2010b): Bidirectional Coupling of Macroscopic Optimization and Microscopic Simulation of Earthwork Processes. Proc. of the 27th CIB-W78 Conference, Cairo, Egypt.

König, M., Beißert, U. (2009) Construction Scheduling Optimization by Simulated Annealing. Proc. of the 26th Annual International Symposium on Automation and Robotics in Construction, Texas, USA.

Kneidl, A., Thiemann, M., Borrmann, A., Ruzika, S., Hamacher, H. W., Köster, G., Rank, E. (2010): Bidirectional Coupling of Macroscopic and Microscopic Approaches for Pedestrian Behavior Prediction. In: Proc. of the 5th Int. Conference on Pedestrian and Evacuation Dynamics. Gaithersburg, MD USA, 2010

Luo, W., Liu, Q., Hu, Z., Qiu, Y. (2008) The Simulation Study on Dynamic Optimization of Hydropower Project Earthwork Allocation System Based on Petri Net. Proc. of the 4th International Conference on Wireless Communications, Networking and Mobile Computing, Dalian, China.

Marzouk, M., Moselhi, O. (2004) Multiobjective Optimization of Earthmoving Operations. Journal of Construction Engineering and Management, vol. 130, issue 1, pg. 105-113.

Martinez, J. C. (1998) EarthMover - Simulation Tool for Earthwork Planning. Proc. of the 1998 Winter Simulation Conference, Washington DC, USA.

Son, J., Mattila, K. G., Myers, D. (2005) Determination of Haul Distance and Direction in Mass Excavation. Journal of Construction Engineering and Management, vol. 131, issue 3, pg. 302-309.

Sung-Keun, K., Russell, J. S. (2002) Framework for an Intelligent Earthwork. Automation in Construction, vol. 12, issue 1, pg. 15-27.

Wimmer, J., Ji, Y., Horenburg, T., Borrmann A., Günthner W., Rank, E. (2010) Evaluation of the 3D Model-based Earthwork Process Simulation in Practice (in German). Proc. of the 14th ASIM-Conference Simulation in Production and Logistic, Karlsruhe, Germany.