An Integrated 3D Simulation Framework for Earthwork Processes

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ABSTRACT: The paper presents a framework that helps in the planning and analysis of earthwork processes in infrastructure construction projects by applying simulation techniques. In contrast to existing solutions, the framework presented here makes it possible to retrieve all the information required to run the simulation in an automatic way from a holistic 3D model that integrates the 3D roadway model, the 3D surface model and the 3D subsoil model. The most important information needed to simulate earthwork processes are the location and the quantity of cut and fill sections. To generate this data, a computational method has been developed that applies a voxelization to the merged 3D model. The result is a large set of cubes, each of which possesses a dedicated position and material. This mass haul data is much more fine-grained than that used in traditional approaches and forms an excellent basis for performing a detailed earthwork process simulation. The employed simulation engine which is based on the discrete-events paradigm, serves to describe entities such as diggers and trucks, their behaviour (e.g. digger fills truck) and the time required for an atomic process step (to fill a truck, for instance). The result of the simulation is a set of detailed information on the utilization ratio of the employed resources and the time required for completing the entire earthwork project. This allows the user to identify bottlenecks and slack periods and adapt the resources accordingly.

1 INTRODUCTION

The earthwork plays a vital role in road construction projects. The planning of certain aspects of the earthwork process, such as the transportation of excavation material and the choice of construction equipments for cutting and filling, is only inadequately supported by the existing IT system. The given solutions that currently function as a planning basis are the 2D vertical and 2D horizontal alignments and the 2D mass profile containing the amount of cutting and filling materials and the approximate positions (centre point) of the cut and fill areas. Many decisions, like choosing the number and the type of excavators and trucks required, are made on the basis of experience from previous projects. However, this often leads to over- or underestimating the capacities needed for the project concerned, which may result in delays or increased costs, respectively.

The main goal of the approach introduced in this paper is accordingly to support the decision process by applying simulation techniques, in order to maximize the efficiency of the resources employed and obtain the best possible ratio between the time and costs invested in completing the project. Potential problems such as bottlenecks or low-efficient activities can be diagnosed in an early stage by simulating the earthwork processes.

In recent years, a number of different simulation concepts and prototypes have been developed, especially in the field of construction project management (Franz 1999, Weber 2007, Beißert et al. 2007, 2008, Chahrour 2007 and König et al. 2007). The first step towards setting up a simulation framework is to acquire data from the real world, using a digital data model.

In road construction, a roadway is traditionally designed using 2D views of the horizontal and vertical alignment coupled with a series of cross-sections along the road axis. This approach allows the civil engineer involved in the road design to concentrate on the major design tasks, like the radius of curvature and gradient and contributes towards reducing the complexity of the design work.

Another requirement is information on the adjacent terrain. This information is encoded in a digital terrain model (DGM), which is generated on the basis of the survey data acquired for the terrain in question. Using the conventional approach, the amount of mass to be excavated or filled is calculated as follows: a cross-sectional profile is
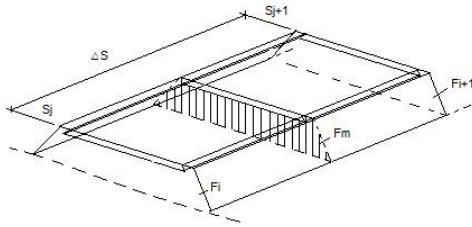
$$V = F_m \cdot \Delta s = \frac{F_i + F_{i+1}}{2} \cdot (S_{i+1} - S_i)$$

Figure 1: Calculation of earth mass between two cross-sections

determined by intersecting the cross-sectional drawing of the road with the digital terrain model. It is within this 2D profile that the areas of the cutting and filling sections are estimated. The volume V of the materials to be excavated or to be filled in between the two cross-section profiles is calculated by multiplying the average cutting or filling areas by the distance between two profiles (Figure 1).

This standardized method of mass-calculation gives the amount of earthmoving involved, the position of the embankment and the section to be cut, respectively. However, it still lacks the following relevant information required for a detailed earthwork simulation:

- the subsoil properties of the materials to be excavated, for example breaking factor or compaction factor. This data is relevant for choosing appropriate construction equipment.
- information on subsoil layers for analyzing the possibility of reusing the excavated material for constructing the embankment.
- the exact locations of the cut and fill sections for a detailed planning of the transportation logistics.

These aspects were taken into consideration to develop a new computational method which provided the amount of earthmoving required and the subsoil properties of cutting materials. The method presented here is entirely based on comprehensive 3D modeling. The main ideas behind this method are as follows: Firstly, a 3D representation will be generated from the 2D views of the existing road design which the 3D information implicitly provides. Secondly, other 3D models involved in the road design, such as the digital terrain model and the subsoil model, can be integrated into the reconstructed 3D road model. The resulting merged model is subsequently analyzed using a 3D evaluation grid.

The new evaluation method is based and a so-called *voxelization*, i.e. it calculates the topological position of each single grid element, a *voxel*, in relation to the boundaries of the layers of the 3D subsoil model and the 3D DGM as well as to the boundary of the road body; and subsequently assigns the respective information to these grid elements, as illustrated in Figure 2. Obviously, a discrete 3D

model of cuts and fills can be generated during the voxelization process. The resulting voxel objects contain several useful attributes like type (cut or fill), geometric position and classification of the subsoil, if necessary. With this method, the quantitative amount of earthwork can be determined and allocated comprehensively for the simulation.
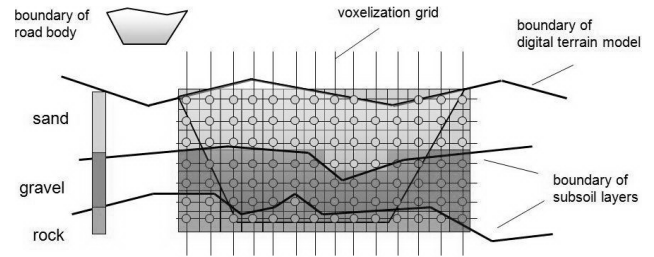

Figure 2: Voxelized cross-section for earth mass calculation regarding to the position and subsoil type of cutting area

Standardized exchange formats are recommended for transferring the data relating to the road design from the computer-aided systems involved. For this reason, the paper presents an overview of the existing formats and compares them regarding their advantages and disadvantages in Section 2.1.

This paper is divided into four parts. While the state-of-the-art of using digital models in road construction and of employing process simulation techniques is introduced in the second section, the concept devised for the simulation framework based on an integrated 3D model will be described in detail in the third section. The fourth section discusses the design and the technical implementation of the developed framework components.

2 THE STATE OF THE ART

2.1 *Digital models in road construction*

The development of digital models in the AEC industry started in the field of building construction. Over the course of the past 15 years, the data exchange standard IFC (Industry Foundation Classes) has been developed to realize the exchange of digital building models (IAI). In an IFC model, not only the logical building structure, the individual building components and their attributes and relationships but also the 3D geometry are represented in an object-oriented manner. Such a model can be used to exchange complex planning data between different construction software applications.

The first attempts to extend the IFC model into the field of infrastructure projects are currently in progress. Recent research and development in this field is marked by the development of the international exchange formats IFC-Bridge and IFC-Road (Yabuki et al. 2003, 2006), and numerous national standards. For example, OKSTRA (Objekt

Katalog für Straßen- und Verkehrswesen) in Germany (OKSTRA) and TransXML (Scarponcini 2006) in the U.S.A. have been set up and implemented in national construction software systems.

The Germany Standard OKSTRA is of particular interest. The entire range of objects that feature in road construction and management are defined in an EXPRESS schema, in particular the rules and
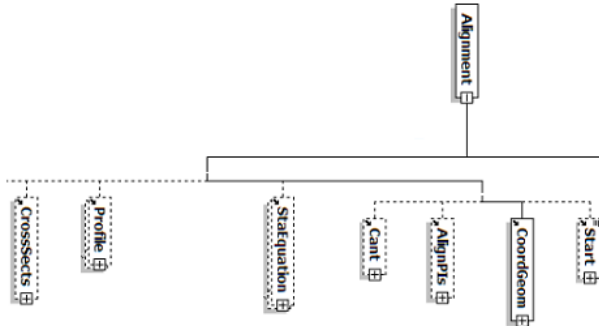

Figure 3: Part of the LandXML-Schema, hierarchical structure of the top-element "Alignment"

regulations in force in Germany with respect to the process of planning, modeling and design of roadways. However, the main shortcoming of the German standard is its inadequate implementation in existing construction software programs.

By contrast, the international standard LandXML, which was set up by the company Autodesk (LandXML), has been widely implemented in today's CAD programs for civil engineering projects. The standard is based on the data exchange format XML (Extensible Markup Language) and structured hierarchically. A part of the LandXML standard is illustrated in Figure 3. The top element, the road alignment, is divided into different subparts including the main road design views in 2D, such as the horizontal alignment ("CoordGeom"), the vertical alignment ("Profile") and the road cross-sections ("CrossSects"). These parts are further divided into subparts that are related to one another, making it possible to describe and depict the geometric and semantic attributes of the road alignment.

The technique of representing a road design in an object-oriented manner is called a road product model (Rebolj & Tibaut 2008). The advantages of the LandXML standard are the wide support provided by computer-aided systems for infrastructure design (Autodesk Civil3D, RIB STRATIS, Obermayer ProVI, and Bentley Inroad) and the flexible extensibility of the LandXML schema. For this reason, the LandXML standard is particularly well suited as a basis model for an integrative development of 3D product model in road construction.

2.2 *Process simulation techniques*

Process simulation techniques can be classified into three categories (Law & Kelton 2000):
- Static or dynamic
- Discrete or continuous
- Deterministic or stochastic

The discrete event simulation is best suited for modeling the construction processes. Different discrete event-based simulation approaches have recently been developed as part of the latest research in this field. One approach is the Petri net-based simulation. This technique, which is named after its inventor (Petri 1962), divides the simulation model into two parts: a static simulation network and a dynamic token system, with the static network consisting of the three element classes: location, transitions and directed arcs.

The locations mark a status. The transitions are the only active components which inherit actions and enable a change in status. There is always a directed arc between a status and a transition. Another rule is that there cannot be two statuses or transitions in succession. The dynamic elements, called tokens, represent the current status of the system. In higher Petri nets there are various tokens which react differently to transitions. The works of Böttcher, Franz, Sawhney and Charour, which aim at simulating construction process, are based on the Petri net technique (Böttcher 1994, Franz 1999, Sawhney et al. 2003 and Charour 2007).

Another simulation technique is the agent-based approach. This simulation model is used to simulate the actions and interactions of autonomous individuals, the intention being to assess their influence on the whole simulated system. In the simulation of the building construction, an agent-based approach has been developed to investigate the efficiency of different involved maintenance systems (Kugler 2008).

In addition, there are also simulation systems that feature a graphic interface and a component-based model generation. In the domain of plant design, several simulator concepts have been established in this manner. It is easy to create a manufacturing process model using the aforementioned simulation components. Commercial simulation systems that are currently on the market include AuToMod, Enterprise Dynamics and Plant Simulation. For example, a simulation toolkit for the shipbuilding processes has been implemented on the basis of the commercial simulation system Plant Simulation (Steinhauer 2008). This toolkit models the essential manufacturing processes in a shipyard using a constraint-based approach. The constraints are used here to determine the best assembly strategy for each ship from the point of view of the costs and the available resources. Moreover, this toolkit has been extended by König et al. for the simulation of

building construction processes (König et al. 2008) by classifying the common constraints into soft and hard constraints. Hard constraints represent requirements that have to be fulfilled to execute a work step, including required resources such as manpower, construction equipment and material, as well as technological dependencies in the construction process. Soft constraints, on the other hand, can be used to model a construction strategy, to avoid soiling in interior fitting processes, for example. Once all the hard constraints have been taken into account and more feasible work steps are available for execution, the soft constraints are used to rank them. Subsequently, the best candidate is chosen. Using Monte Carlo techniques for randomly choosing the next executable work steps enables the generation of an optimized process sequence (Beißert et al. 2008).

In Weber's Work, a component-based simulator has been applied to analyze the material flow on construction sites. In this simulator, a set of construction equipment and construction setups are modeled as simulation components, like trucks, cranes and storages (Weber 2007).

A current trend in the application of simulation software is to change the method for obtaining time values for the simulation. In conventional simulation design techniques, macroscopic reference values are often used to describe the work output, such as "one worker can create 200 square meters per hour". The new method has been devised to acquire the time values in a "bottom-up" approach. The individual movements of a machine are described physically so that events are created by controlling the electro-mechanic machine and the activities of the respective workers (Wagner 2008).

3 THE CONCEPT OF THE SIMULATION FRAMEWORK

3.1 Concept Overview

The simulation framework mainly consists of two essential components (Figure 4):

1 The *Integrator* merges the available models retrieved from different fields of road construction into a holistic 3D road model, and calculates the amount of the cut and fill earth masses by applying the *voxelization* method on the integrated model. Each subsoil layer of the subsoil model is identified using a unified identifier linked to the subsoil properties (breaking factor and compaction factor) which are stored in an external geotechnical database. The source data for the simulation is then exported into an XML File.

2 The *Simulator* generates a model for the earthwork activities based on the project schedule, and then imports the estimated quantities of cutting and filling materials from the *Integrator* using the XML file introduced above. Additional data, such as information on machine equipment, will be imported from a construction machine database. Finally, the earthwork processes are simulated using a discrete-event simulation engine.

As result of the simulation, an optimized project schedule and a report on the allocation of the involved resources, for example, the working efficiency of construction equipments are generated. The updated project plan can be now imported back into the *integrator* as input. By combining the actual
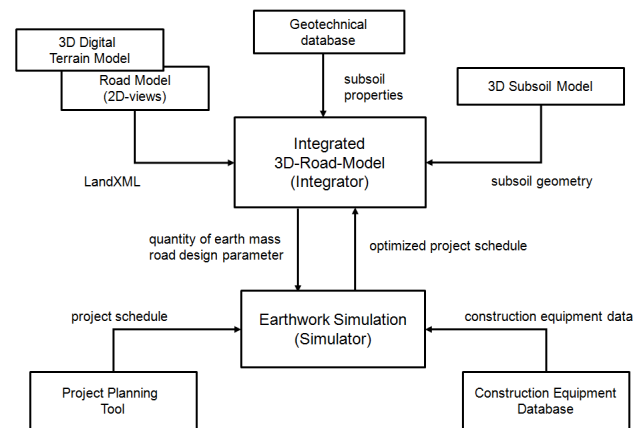

Figure 4: The structure of the simulation framework

project schedule with the integrated 3D road model, the whole road construction progress is visualized as a 4D model. The final objective of our approach is to realize that, with the support of this framework, a civil engineer can make the whole planning process of the earthworks in a road construction project in a simple and intuitive way. The following sections will describe the structure and design of the *Integrator* and the *Simulator* in greater detail.

3.2 Generation of simulation source data

3.2.1 Design and implementation of the integrator

The *integrator* shows a modular architecture (Figure 5). The foundation is formed by a geometry kernel, which provides the basic geometrical representation of the vertical alignment, the horizontal alignments and the cross-sections, as well as the basic functions required for the generation of an integrated 3D road model. After importing the LandXML file, the original 2D road geometry and additional information on the road construction is converted into the kernel's internal geometric objects. In the next step, the *integrator* generates the 3D road model implicitly provided by the 2D road views. The 3D digital terrain model described as a triangulated surface model in LandXML can then be

integrated automatically with the 3D road model without preprocessing.

The subsoil model contains various subsoil layers. Each subsoil layer is made up of 3D triangular mesh with a similar structure to the 3D digital terrain model, and identified by means of a unified identifier. Normally, the subsoil structure is modeled by a geotechnical engineer using drilling profiles and lab investigation results of the soil sample drilled out at certain selected locations. The subsoil model is then created using a specific program for subsoil engineering, such as Surpac (Gemcom), for example.

Voxelization:

1. Find the bounding box *bbox* of the 3D road model
2. Triangulate the 3D road model
3. Check the intersection of all surface triangles of subsoil and the digital terrain model with *bbox* and keep the intersected triangles (to reduce the number of the triangles) in array *triangle_global*
4. Divide the 3D road model into sections based on the cross-sections
5. Iterate each section i,
   5.1 Find the bounding box *bbox_part* of the section i
   5.2 Find the triangles from *triangle_global* intersecting with the *bbox_part* and store in array *triangle_local*
   5.3 Sub-routine: *FindVoxelCandidate*
   5.4 Iterate the *voxel-candidate* array
      5.4.1 Validate the geometric position of the center p of the voxel candidate j
      5.4.2 If p is topological above the triangulated road body contained in the *bbox_part* and below any triangle in the array *triangle_local*, a cut-voxel has been found.
         5.4.2.1 Sub-routine: DetermineCutVoxelType
      5.4.3 If p is topological under the triangulated road body and above any triangle in the array triangle_local, a fill-voxel has been determined.
6. end of iteration

FindVoxelCandidate:

1. Divide *bbox* with a discretization degree of 2 at a predefined depth (for example, depth $6 = 2^6 = 64$ divisions) and assess whether the divided sections intersect with the *bbox_part*.
   1.1 If so, then division should be continued until the degree of detail of the analysis grid is achieved. The resulting discretization is then be stored in the array *voxel_candidate*.

DetermineCutVoxelType:

1. Iterate all relevant triangles of subsoil layers
   1.1 Find the layer *s*, above which the designated voxel is positioned directly, then assign the type of material from the layer s to this voxel.

Figure 6: Voxelization algorithm in pseudo-code

The exchange of the subsoil geometry is realized using ASCII files. The geometry of a subsoil layer is exported into two ASCII files affiliated with one another. The first file stores the 3D points of a subsoil layer boundary. Each point is identified with an integer number. In the second file, each triangle is stored using three references to the identifier of the first file. The subsoil properties of the layer are queried from a geotechnical database using the layer identifier. Therefore, the 3D road model, the 3D digital terrain model and the 3D subsoil model are merged and visualized in the model integrator. The other two key components of the *integrator* are the mass calculator and the output generator for simulation source data. Since these two modules realize the essential functions of the *integrator*, the algorithm of the *voxelization* method will be explained in detail in the following chapter.

3.2.2 *Voxelization Algorithm*

The voxelization algorithm determines the amount of material to be excavated or filled through discretization of the integrated 3D model using a 3D grid. The voxelization algorithm is presented in pseudo-code (Figure 6)
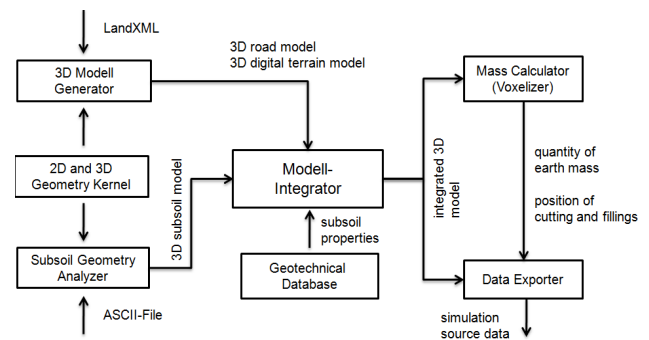

Figure 5: The architecture of the integrator

The width of the analysis grid, that determines the size of a single voxel-element, can be arbitrarily chosen by the user. The smaller the size of the voxel, the more precise the calculation will be. On the downside, the calculation duration will be prolonged significantly. First experiments have shown that a voxel size of 0.5m x 0.5m x 0.5m yields acceptable computation times and at the same time simulation input data with suitable accuracy.

3.3 *Event-based earthwork simulation*

Different types of input data are required to simulate an earthwork process. This data is prepared for simulation in the pre-processing module (Figure 7). After the preparation stage, the earthwork simulation module is charged with the data and feeds it into a discrete event simulation engine. In the post-processing module the results of the simulation runs are prepared for the 4D visualization. The paragraphs below describe the diverse modules in detail.

The machine and equipment for carrying out the earthworks are chosen in the pre-processing module. All machine data connected with performing the simulation is imported from a machine database, the Equipment Information System (EIS) (Günthner et al. 2008). The datasets of more than 5000 construction machines are stored in the database. Every machine is classified by the import routine and the data is made available for the subsequent simulation process. The next step is to import the road design data from the *Integrator*. This supplies the information about the excavation and filling areas and their relevant geometric position.
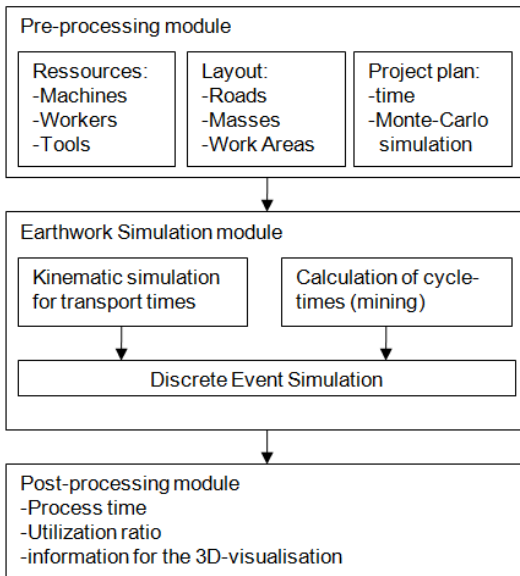
Figure 7: module structure of the simulator

To reduce the amount of data resulting from the voxelization method, the voxels are reconfigured to several zones for the earthwork. The advantage of this approach is its flexibility. The voxels can be assembled differently in different simulation runs to optimize the earthwork process. Since the *integrator* only provides details of the amount of earth, the auxiliary roads used for transporting the earth masses have to be generated in the *Simulator*. A graphical interface is employed to facilitate the creation of auxiliary roads.

A project plan is imported to find out when individual processes should begin. The preprocessing module is used to convert the static project plan into a format interpretable by the simulator, i.e. a corresponding event is created for every start and end point of a process. If the user wants to do a statistical covering of the project plan, he is able to define a minimum and a maximum duration for every single process. With this information the preprocessing module is able to run a Monte Carlo simulation to evaluate the statistical security of the planned schedule and detect critical processes of the whole project. If any critical earthwork processes are detected, a detailed discrete event simulation is started using the earthwork simulation module.

The first step in the earthwork simulation module is to generate an activity. This activity must be linked to a specific process of the project plan. Furthermore the cycle times of the earth working machines have to be determined. Classical calculation algorithms, as presented in (Bauer 2006), can be used for this purpose. The parameters for the calculation are the machine data, on the one hand, and the ground data provided by the *integrator* for
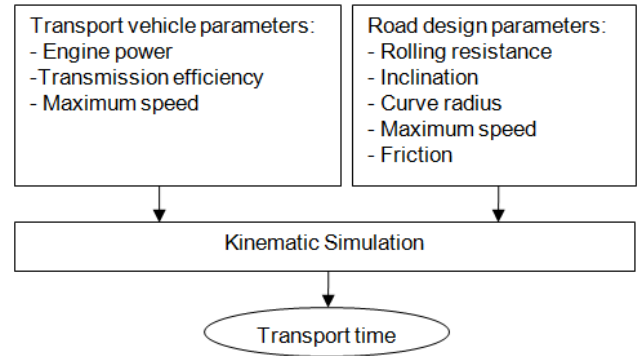
Figure 8: parameters for the kinematic simulation

each individual voxel, on the other hand. Special parameters for the earthwork simulation are the transport cycle times. In this case the calculation methods of the literature are not used, because they are not detailed enough to model the different transport vehicles. A kinematic simulation has been created as a new way to determine the transport times.

As shown in Figure 8, a kinematic simulation is set up with the parameters of the road segments and the parameters of the vehicle to determine the cycle times. With all this information it is now possible to perform a discrete event simulation of an earthwork process. The results of this simulation are reprocessed by the post-processing module. The duration of the earthwork process resulting from the detailed simulation is used to update the project schedule. In this way the effects of changes in the schedule can be evaluated again using the Monte Carlo simulation.

Furthermore the utilization ratio of all resources can be shown. The resources - not only machines and workers but also roads and workspace – can be visualized. With this information, the bottlenecks in the earthwork process can be found. In addition to that, the resources can be linked with costs, so that the whole costs of the earthwork processes can be determined. The simulation results are displayed to make it easier to understand the processes. For this purpose, the results are returned to the integrator to depict the work progress in 4D.

With this concept, the *simulator* is able to simulate and visualize different earthwork processes in combination with the *integrator*.

4 FUTURE WORK

The implementation of the presented simulation framework is already completed. The next step will be to try to evaluate the framework with the help of a real construction project. The feasibility of this framework will be analyzed by comparing it with the technical data and interviews with professional planers and constructors.

In the *Integrator* part, the further development focuses on optimizing the earth movement based on the integrated 3D model. To date, the *integrator* provides the *simulator* with details of the amounts of earth involved. However, every possible transportation route between cut, fill, dump and temporal storage has to be tested in the *simulator* to find an optimal mass-haul balance. Also, the reusability of the excavated materials for fill areas is not taken into consideration.

In current earthwork planning practice, one of the most important tasks is to optimize the mass-haul balance, because both the purchase of material for filling and the recycling of excavated materials is very expensive. At the same time, from the point of view of transport logistics, it is possible to reduce both the cost and time involved in transportation by optimizing the transport routes. For these reasons, an optimization process will be integrated to find the optimal allocation of the earth masses in terms of the constraints described above.

In the *simulator* part, in order to enhance flexibility in the generation of earthwork activities, a constraint-based approach will be applied with the discrete-event based simulation engine. Other focal areas are to create earthwork-specific simulation components, like compaction processes and embankment construction processes, while taking more kinematic influence factors into consideration.

5 CONCLUSION

In this paper, a 3D model based simulation framework for earthwork simulation has been introduced. The advantages of this framework are: Firstly, the data from the road planning can be reused for earthwork simulation. Secondly, the voxelization method guaranties an accurate calculation and positioning of earth masses to be excavated or to be filled. Thirdly, the discrete-event based simulation can directly use the simulation source data provided by the *integrator* to optimize the project schedule and support the earthwork planning process.

The framework has been completely implemented, in the next step, the applicability and usability of this framework will be evaluated with a real road construction project.

6 ACKNOWLEDGEMENTS

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