ForBAU – The virtual construction site project

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ABSTRACT: The paper introduces the Bavarian research cluster ForBAU which has been launched in January 2008 with the aim of an improved planning and management of construction sites, especially in infrastructure projects. To realize this goal, the research cluster focuses on developing a virtual representation of the construction site which involves all essential aspects, including models of the buildings under construction, the environmental boundary conditions, the construction procedure, the logistics processes, and the required resources. The resulting virtual construction site forms one the one hand the basis for simulating the construction process, which allows to identify critical aspects of the construction project in advance and to adapt the resources and the scheduling accordingly. On the other hand, the holistic virtual representation of the real construction site is used during the execution phase to capture all available information about the project – enabling site managers, controllers and engineers to get a detailed overview on its progress and identify potential problems in an early stage.

1 INTRODUCTION

1.1 *Overview and global objectives*

In January 2008 the Bavarian research cluster ForBAU "The virtual construction site" has been launched. The project has a duration of 3 years and is funded by the Bavarian research foundation with 2.25 Mio Euro. 14 researchers from 6 research units are involved, including the Construction Informatics Group at the Technische Universität München, the Center of Geotechnics at the Technische Universität München, the Chair for Materials Handling, Material Flow and Logistics at the Technische Universität München, the Institute for Robotics and Mechatronics at the German Aerospace Center (DLR), the Construction Informatics and the Surveying groups at the Fachhochschule Regensburg and the Chair for Logistics at the University Erlangen.

In the project, more than 30 industry partners are involved, including major construction companies, planning offices, surveying services providers and construction machine manufacturers. The partners provide expert knowledge about the current practice in their specific domain. They consequently take part in the development of solutions driven by the researchers of the cluster, and help to evaluate them in real-world projects.

ForBAU focuses on infrastructure projects, i.e. the planning and realization of roadways and bridges contained therein. Accordingly, the construction processes investigated by the research cluster are earthworks processes and bridge construction processes. One of the major objectives is to realize a continuous data flow from the planning into the execution phase. This is realized by means of a virtual representation of the real construction site. In the proposed concept, this *Virtual Construction Site* created in the planning phase subsequently forms the basis for planning the construction processes and the related logistics processes. The digital model is fed with real-world data during the execution phase, including information about the current progress of the construction project as well as quality control-related information, for example.

1.2 *The project structure*

The ForBAU project is structured into 4 different subprojects (Figure 1). Subproject 1 "BAU-IT" deals with the development of IT solutions that form the basis for realizing the virtual construction site. Main research aspects are the integration of modern survey methods such as airborne and terrestrial laser scanning as well as the creation of a holistic 3D model comprising the 3D terrain surface, the 3D roadway, 3D bridge models, the 3D subsoil model and 3D models of the major site equipment. Besides, SP1 focuses on the technical realization of the centralized storage of this virtual construction site model which includes the diverse 3D models as well as any additional non-geometric data. Another aspect is to derive input data from this model for the process simulation which is realized within subproject 2.

Subproject 2 “BAU-SIM” deals with the simulation of the earthwork and the bridge construction processes. Using a discrete-event simulation engine, a detailed simulation of individual work steps is performed, taking into account not only technological dependencies between individual work steps but also the available resources.

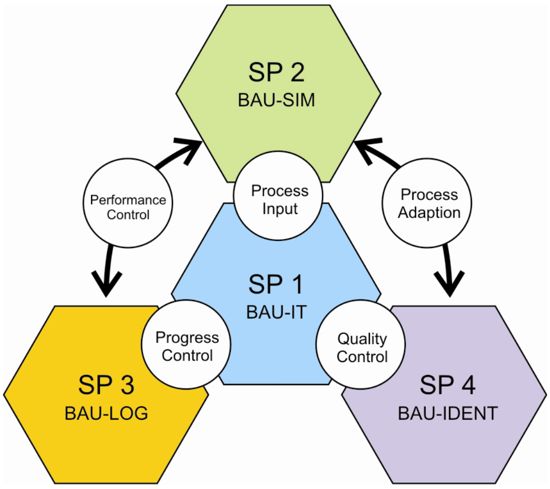


Figure 1. The ForBAU project is structured into 4 individual subprojects

The results of simulation include the predicted project duration as well as detailed information about the utilization ratio of the employed resources. This allows identifying potential bottlenecks as well as detecting under-utilization of resources and thus provides means for optimizing the project’s costs.

Subproject 3 “BAU-LOG” aims at integrating logistical processes into the virtual construction site. In the planning stage, the simulation results from SP 2 are used to precisely determine delivery dates for materials and special equipment. Also, logistical processes such as the transportation of earth from and to the construction site form part of the simulation concept. During the execution of the construction project, modern logistical technologies such as digital bills of delivery are employed in order to feed the digital construction site with real-world data.

The same goal is pursued by Subproject 4, which investigates how identification technologies can be used to keep track on the materials delivered to the construction site. The employed identification technologies include traditional approaches such as barcodes, but also the modern version subsumed under the acronym RFID.

2 SUBPROJECT 1 – BAU-IT

2.1 *Overview*

Subproject 1 “BAU-IT” forms the central part of the entire ForBAU project and deals with the development of IT concepts and tools for realizing the virtual construction site.

One of the major aspects of the work in SP1 is the complete 3D modeling of the construction project. In this regard, we identified the following essential sub-models (Figure 2):

- 3D Terrain Model. A 3D description of the terrain before the project starts.
- 3D Building Model. The 3D model of the buildings to be constructed. Since ForBAU focuses on infrastructure projects, the modeled buildings are mainly bridges, but also geotechnical buildings such as retaining walls.
- 3D Roadway Model. The 3D model of the roadway to be constructed.
- 3D Subsoil Model. A 3D representation of the subsoil, i.e. a description of the soil layers and their boundaries.

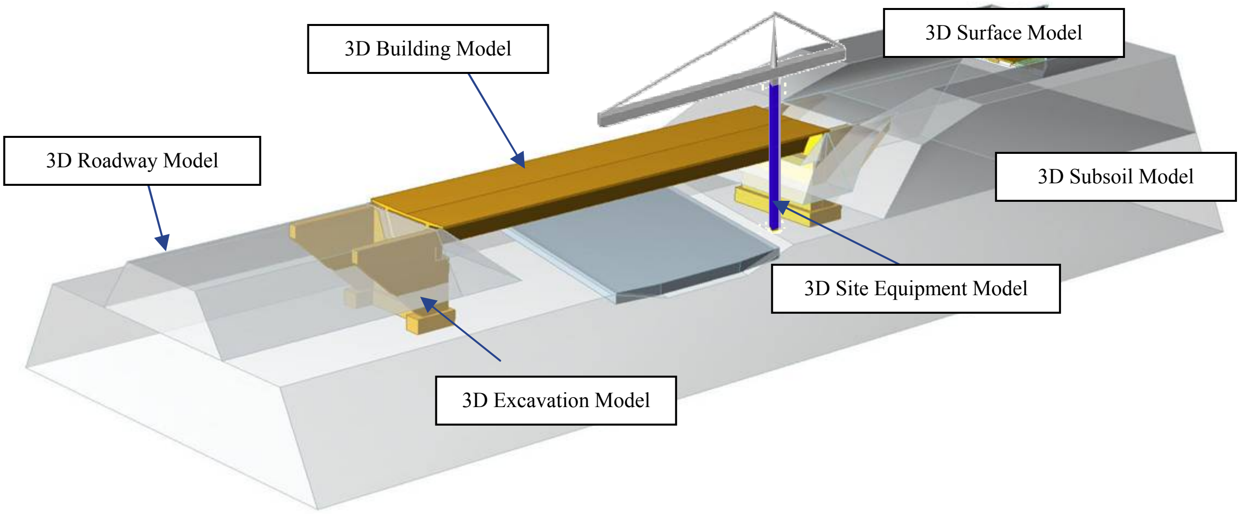


Figure 2. The 3D sub-models of the virtual construction site.

- 3D Excavation Model. A model of the temporary excavation pits which are created to build the bridge's abutments, for example.
- 3D Equipment Model. A 3D model of special equipment used to erect the bridge(s), e.g. a crane.

In the construction industry these diverse 3D models are usually generated using completely different modeling tools. One of the major challenges is therefore the integration of these sub-models into one holistic model. To this end, the ForBAU integrator has been developed which is discussed in more detail in Section 2.6.

2.2 *The 3D Terrain Model*

In the ForBAU project, modern survey methods are employed for capturing the site terrain before the construction works start. Here, the aim is to simplify and automate the site survey. On the other hand, survey methods are also applied during the construction process, in order to enable an automatic detection of the construction site's progress. Finally they are used to control the quality of erected buildings.

The employed methods are terrestrial and airborne laser scanning as well as stereo-photogrammetric surveying. In the former case, members of Fachhochschule Regensburg compare commercially available laser scanning technologies with respect to costs and applicability in the field.

In the latter case, the Institute for Robotics and Mechatronics at the German Aerospace Center (DLR) is developing a new high-resolution stereo camera that realizes a precision up to 2 cm (Börner et al., 2008). The camera can be mounted on micro air vehicles (MAVs) such as the Octocopter depicted in Figure 3 (Gurdan et al., 2007). The use of MAVs allows to realize laser scans of large areas in a much more cost efficient way than by using planes or helicopters.

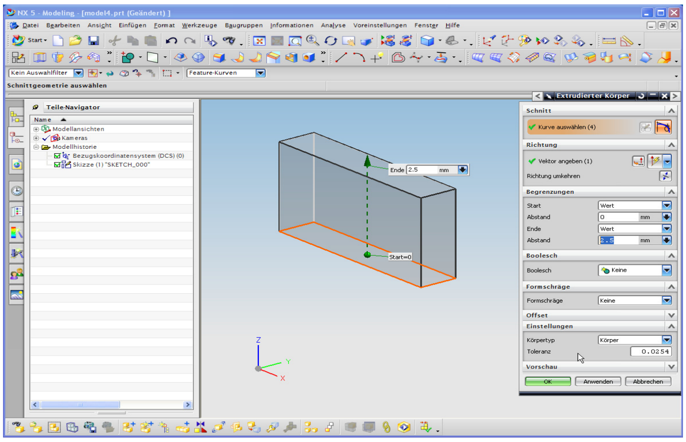
Figure 3. Octocopter developed by DLR, carrying a stereo-photogrammetric camera.

One of the major challenges in the context of the virtual construction site is to achieve a mainly automatic processing of the surveying data, starting at the point clouds generated by either laser scanning or stereo-photogrammetry, and resulting in a complete 3D volume model. To this end, on the one hand existing commercial solutions are applied, and on the other hand new computational methods are being developed (Hirschmüller, 2005).

The 3D terrain model forms the basis for the roadway planning activities. In case of infrastructure projects, it is usually created from surveying data using roadway planning tools.

2.3 *The 3D Bridge Model*

Since bridges form part of the roadway, a bridge's geometry strongly depends on the roadway's course, i.e. its axis, width, and cross slope. Often, small changes in the roadway's design occur during the planning process. When a traditional CAD system is used to create the 3D model of a bridge, these modifications require a laborious manual adaption of the bridge's geometry. Therefore the ForBAU researchers have been investigating parametric CAD technology (Sachs et al., 2004), which allows to explicitly model dependencies between geometric objects (Figure 4). Binding the bridge to the roadway axis in this way enables an automatic update of the bridge's geometry whenever modifications of the roadway become necessary.



NX 5 - Modeling - [model4.prt (Geändert)]

Kein Auswahlfilter

Feature-Kurven

Schnittgeometrie auswählen

Teile-Navigator

Name

Modellansichten

Kameras

Modellhistorie

Bezugskoordinatensystem (DCS) (0)

Skizze (1) "SKETCH_000"

Ende 2.5 mm

Start=0

Extrudierter Körper

Schnitt

Kurve auswählen (4)

Richtung

Vektor angeben (1)

Richtung umkehren

Begrenzungen

Start Wert

Abstand 0 mm

Ende Wert

Abstand 2.5 mm

Boolesch

Boolesch Keine

Formschräge

Formschräge Keine

Offset

Einstellungen

Körpertyp Körper

Toleranz 0.0254

Vorschau

Figure 4. Parametric modeling using Siemens UGS NX

In any case, bridges are geometrically complicated structures (Katz, 2008). They are often located in a curve (resulting in a cross slope) and at the same time in a longitudinal camber. This results in a highly complicated three-dimensionally curved surface of the superstructure (Figure 6) and implies high requirements on the CAD system's capabilities to model freeform surfaces. Preferably, the CAD system should provide the possibility to use non-uniform rational B-spline (NURBS) patches to model the bridge's surface.

A complete list of the requirements on a CAD system for the 3D modeling of bridges is depicted in Figure 5.

Since in the moment there is no AEC CAD product on the market that fulfills these requirements, we decided to employ a system from the mechanical engineering domain, namely Siemens UGS NX. The

3D modeling
Volume modeling
Freeform surfaces
Parametric modeling
Object-based modeling
Predefined AEC objects
Modeling of reinforcement
Native modeling of clothoids
Generation of code-compliant drawings
Support of AEC data exchange standards
Connection to CAM systems
Connection to structural analysis programs
Large extensions (up to 10km)
Geo-referenced coordinates

Figure 5. Requirements which the 'perfect CAD system' for bridge engineering must fulfill.

system provides parametric and feature-based design, freeform surfaces, a powerful geometry kernel able to perform complicated intersection operations, and a link to Computer-aided Manufacturing (CAM) systems.

However, the fact that NX is a mechanical engineering CAD system implies some problems for the intended use in civil engineering projects. The general shortcomings include

- missing support for modeling reinforcement
- missing support for the creation of drawings that comply to AEC regulations
- missing links to structural analysis programs used in civil engineering
- no libraries of predefined construction objects (walls etc.) available

With respect to roadway and bridge modelling there are some more specific deficiencies of UGS NX:

- no support for a direct modelling of clothoids (spiral sections)
- limited extensions: the NX coordinate system can only handle values up to 1 km
- no possibility to use geo-referenced coordinates (values too large)

However, since there is no CAD program available in the moment that provides perfect support for bridge design, the researchers decided to continue employing NX and taking advantage of its powerful parametric, feature-based modelling engine.

Future work in this area will concentrate on employing the upcoming data exchange format IFC-Bridge (Yabuki et al., 2006) by realizing an export facility into this format.

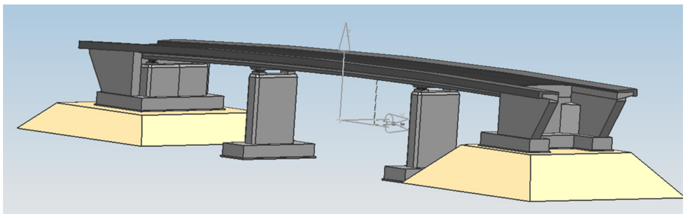


Figure 6: The complete bridge modeled using UGS NX.

2.4 *The 3D Roadway Model*

For designing roadways we follow the classical approach which is based on three different 2D views: the vertical alignment, the horizontal alignment (also referred to as profile) and a number of cross sections (Figure 7).

Using 2D views which implicitly describe a 3D model is a well established methodology in roadway engineering. It helps to reduce the complexity of designing a roadway in 3D space by allowing the engineer to concentrate on the essential aspects in the respective 2D view. Also, all roadway regulations and the major exchange formats (LandXML, TransXML, OKSTRA) are based on this methodology. For these reasons, the developed concept does not recommend to employ a full 3D CAD system, such as UGS NX, but instead one of the many full-grown programs available on the market specifically developed for roadway design, such as AutoDesk Civil3D, Bentley MX Road or RIB Stratis, to only name a few.

Since one of the major goals in SP1 has been the realization of a parametric linkage between the roadway and the bridge geometry, this functionality had to be developed using an intermediary software tool. This tool is the ForBAU integrator presented in detail in Section 2.6.

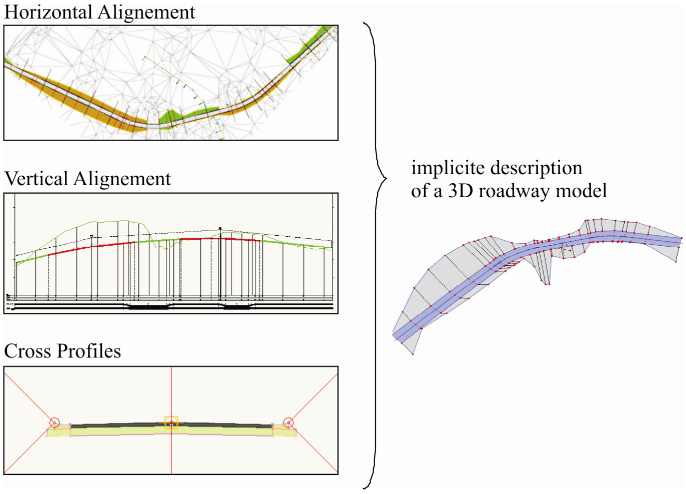


Figure 7. The classical methodology applied in roadway design: Three 2D views define implicitly the 3D model of the roadway.

2.5 *The 3D Subsoil Model*

The 3D subsoil model is a description of the subsoil layers or, more precisely, their boundaries in 3D space. On the one hand it enables a detailed determination of the type and volume of the earth to be excavated and thus allows for a more precise simulation of the earthworks. Also it provides the basis for supporting the decision process of choosing suitable machines. On the other hand it allows geotechnical software can make use of the 3D subsoil information to perform the necessary computations.

The 3D subsoil model is created by interpreting the drill holes gained from locations around the construction site and performing an interpolation between these drill holes (Figure 8). Since the exact shape of the layer boundaries between the drill holes is not known, the 3D subsoil model represents an es-

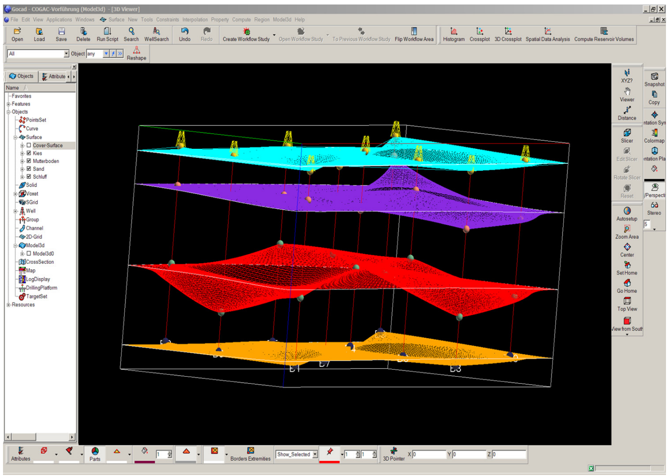


Figure 8. The 3D subsoil model.

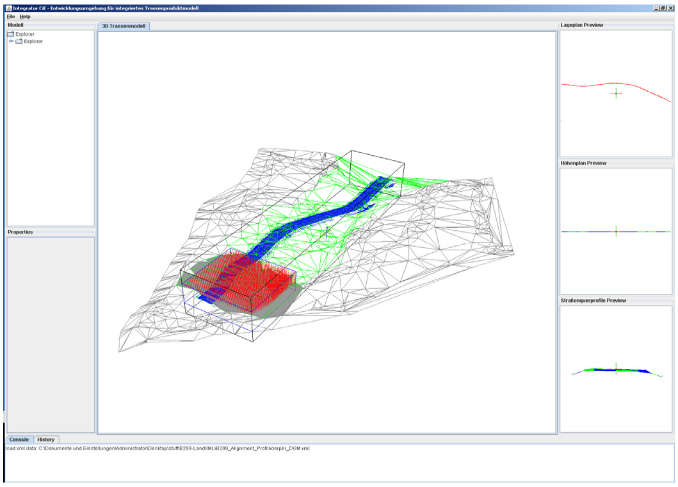


Figure 10: Screenshot of the ForBAU integrator, which merges the 3D models and evaluates them by performing a voxelization to create input data for the earthworks simulation.

timation rather than exact knowledge. This is taken into account by choosing a probabilistic model created by applying Kriging techniques (Chiles & Delfinger, 1999). However, for sake of simplicity, whenever the 3D subsoil model is exported and integrated into the virtual construction site, deterministic layer boundaries are used.

2.6 *The ForBAU integrator*

The ForBAU integrator is a software tool developed by the ForBAU researchers. It offers four important functionalities (Figure 9):

- It realizes the merging of the diverse 3D models originating from different design tools into one holistic model.
- It realizes the parametric connection between the roadway model and the bridge. To this end, 3D reference lines are created from the 2D roadway information and exported into the CAD system UGS NX. The bridge model is then constructed by referencing these lines. As soon as changes in the roadway occur, the integrator updates these reference lines, and subsequently the entire bridge design is updated.
- It creates input data for the earthwork simulation performed in subproject 2 by evaluating the merged model using a 3D grid and applying a voxelization (Figure 10). This functionality is described in detail in (Ji et al., 2009).
- It provides an interface to the Product Data Management (PDM) system employed to centrally store and manage all construction site-related data including the 3D models.

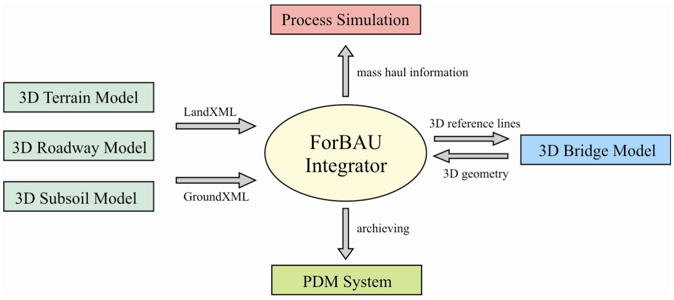


Figure 9. The ForBAU integrator merges the different 3D submodels, creates input data for the simulation of earthwork processes, realizes the parametric coupling between roadway model and bridge model via reference lines, and provides an interface to the PDM system.

The integrator is an essential part of the ForBAU IT infrastructure. Where available, the data exchange has been realized using standardized file formats. For exchanging 3D subsoil data, the format GroundXML has been developed (Obergrießer et al., 2009).

2.7 *Product Data Management System*

To realize a central storage and management of all data related to the virtual construction site, the usage of a product data management (PDM) system is investigated within ForBAU (Borrmann et al., 2009). The PDM technology is well established in the automotive and mechanical engineering domain. The principle idea is to centrally store all CAD models and associated information of a product under development and give the user the possibility the associate these documents with each other. PDM systems provide a number of very useful functionalities to realize concurrent engineering. These include:

- Revision management. Whenever a user has changed a CAD file or any other document, a new revision is generated. This allows to keep track of the modifications, i.e. of the modifying users as well as the modification dates.
- Concurrency control. When a user *A* opens a document, it is locked for any other users, i.e. they are not allowed to modify it until user *A* closes the document.

- Workflow management. The workflow engine integrated within the PDM system allows to automatically process a workflow. For example, users responsible for the next step in a workflow are notified via email when the preceding step has been finished. The system administrator is able to setup workflows customized to the requirements of the respective company.
- Access rights management. A fine-grained rights management allows to define in detail the user's roles, their access and modification rights.
- CAD file preview. The PDM client software provides a preview functionality that enables the user to see the contents of CAD file without the need to open it (Figure 11).

It is important to note that the technological basis of a PDM system is a document management system, and not a product model server (Kiviniemi et al., 2005). This implies some problems, especially with respect to the management of 3D CAD models. CAD systems of the mechanical engineering domain store the models within a multitude of files, each of which representing an individual part. This fine storage granularity facilitates the re-use of these parts and allows at the same time a high degree of concurrency: When PDM users start to modify a part, only this part is locked and not the entire model.

However, CAD systems employed in the AEC domain usually store the entire model within one monolithic file. In this case, the entire model is locked during a modification. Since typical modification cycles take up to several days, the degree of concurrency becomes unacceptable for use in real-world AEC design processes. Technologies to extract partial models from the full model available in product model servers are not provided by PDM systems. Also the handling of non-geometric data is only loosely supported by PDM systems.

Other remaining problems that hamper the use of PDM systems in the construction industry are the rigidity of the workflows and the unsolved question of the ownership of a PDM system. In contrast to the automotive industry, the AEC industry is fragmented into small and medium-sized companies which dynamically form 'virtual enterprises' for each individual construction project. In current practice, none of the participants would agree to share all internal documents and CAD models with all partners.

Finally, a high effort for adapting a PDM system to the requirements of a particular company is necessary. This is acceptable for the stationary industry, where stakeholders and process chains remain fixed over a long period, but not for the AEC industry where each new project would require another adaptation of the PDM system.

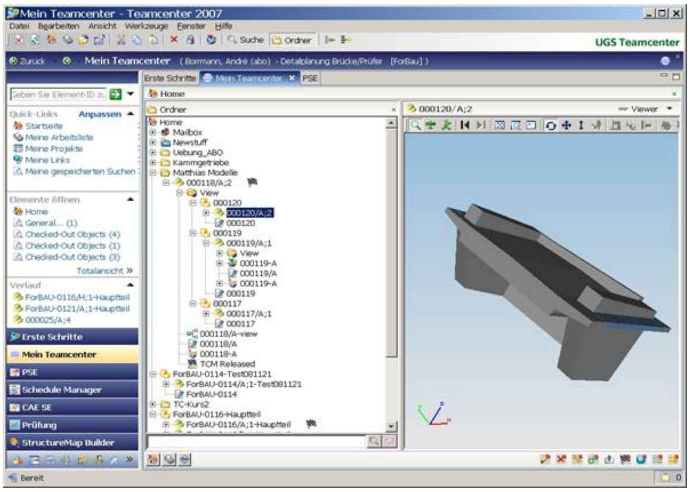


Figure 11. The client application of the PDM system.

3 SUBPROJECT 2 – BAU-SIM

Subproject 2 focuses on the one hand on applying simulation techniques to plan and optimize the construction process in the planning stage. On the other hand it develops methods to update the estimated project plan with the real project's progress during the execution phase.

Two different types of construction processes are simulated: earthwork processes and bridge construction processes. In both cases, a discrete-event simulation engine is used, which has been originally developed for plant layout. However, due to diverging nature of the investigated processes, different approaches have been followed.

In the case of the earthwork simulation, the classical discrete-event simulation methodology is applied (Günthner & Kraul, 2008), i.e. the employed machines such as diggers and trucks are modeled as modules of a fixed process chain (Figure 12). During a simulation, the digger module starts digging and filling a truck as soon as a truck arrives at the digger's position. The duration of this process step is computed on the basis of the digger's characteristics

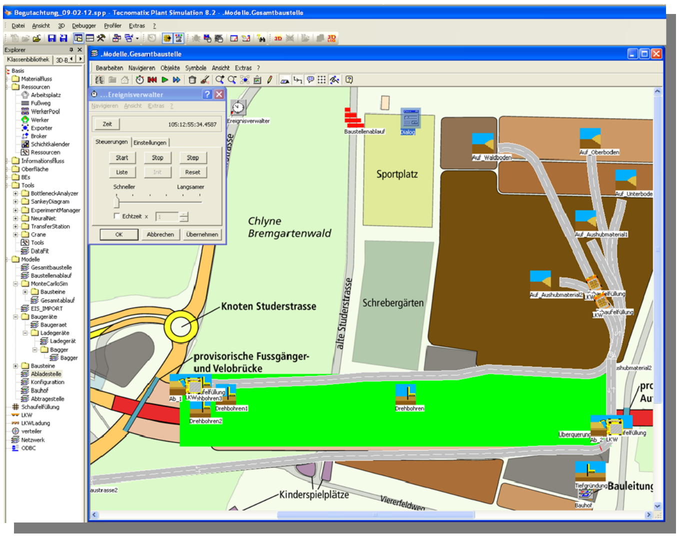


Figure 12: Earthwork simulation using a discrete-event simulator.

and is subject to stochastic variations. The digger stops as soon as the truck is completely filled. In this classical approach, the process chains are rigid, in the sense that the sequence of the work steps is fixed. This is suitable for simulating earthwork processes, but in bridge construction a more flexible approach is required.

For simulating the bridge construction process, the constraint-based methodology developed by Beißert et al. (2008) has been applied. This methodology is also based on a discrete event simulation but introduces additional flexibility in the workflow by selecting the work step to be executed next in a dynamic way. The pre-requisites to execute a work step are modeled using constraints. These include the required material, work force, machines and additional equipment as well as any technological requirements. Since the definition of these constraints for each individual work step and all bridge components is laborious and time-consuming, a software tool called preparator has been developed that allows to assign pre-defined process pattern to the individual parts of a bridge (Wu et al., 2009). From these, the preparator automatically generates the necessary constraints which are fed into the simulation engine.

Using the constraint-based approach, in each discrete time step the next executable work step is chosen randomly from a candidate list. To optimize the work step sequence, a Monte-Carlo procedure is performed, i.e. the entire bridge construction simulation is run multiple times. Each individual simulation results in different work step sequences and thus diverging resource consumption and project duration. An optimized process is identified by evaluating the results of the Monte-Carlo procedure.

As stated above, the second major goal of SP 2 is to capture the current stage of the construction progress in a mostly automatic way. This allows a continuous comparison between as-planned and as-is project state. To this end, the survey methods presented in Section 2.2 and the material flow information gained in subproject 3 and 4 are employed (Figure 13).

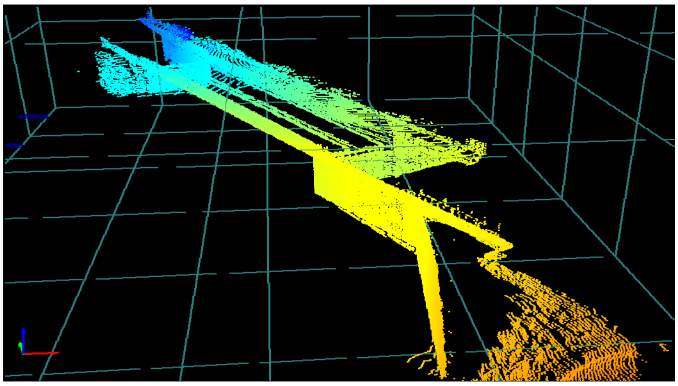


Figure 13. Point cloud gained from a terrestrial laser scan of a bridge. Evaluating the point cloud allows to perform comparisons between the as-built and as-planned geometry, thus realizing quality control. Printed by courtesy of Christofori Ingenieurbüro.

4 SUBPROJECT 3 – BAU-LOG

Sub-project 3 "BAU-LOG" monitors collaborative supply-chain processes relying on information derived from the virtual construction site model to enhance the management of these processes. This includes transferring best practice Supply Chain Management methods developed in other industry sectors to the building industry. One of the main challenges is to adapt them to the branch-specific peculiarities of construction engineering, especially the mobile and temporary characteristic of construction sites.

Within the subproject a decision support system (DSS) is being developed that helps in optimizing the logistical processes including the material flows from and to the construction site, the internal material flows as well as the placement and the utilization ratio of storage places. The system assists the planner in choosing transportation means and routes, as well as in the planning of delivery dates. The DSS is fed with data from subproject 1 (the required amounts of material, the amount of earth to be transported to deponies, etc.), as well as subproject 2 (the simulation results determine the optimal point in time for a delivery).

Another focus of subproject 2 is the control of the logistical processes during the execution of the construction project. Using the data obtained in the subprojects 2 and 4 about the current progress of the construction site and the delivered materials, the logistical processes are monitored and, in case of variances, warnings are generated. Subsequently, the DSS creates alternatives which are proposed to the logistics controller.

5 SUBPROJECT 4 – BAU-IDENT

Subproject 4 "BAU-IDENT" aims at utilizing identification technology to permanently update the virtual construction site with real-world data during the execution phase. The automatic capturing of this data avoids the error-prone and tedious manual gathering as realized at today's construction sites, and offers a much higher timeliness.

Investigations have shown that the radio-frequency identification (RFID) technology is the most promising technology for use on construction sites, since it is resistant against weather, variation in temperature, mechanical exposure and soiling.

The subproject exemplarily investigates how construction machines and auxiliary means can be equipped with RFID chips, including bore hole tubes, formwork panels and drill machines. The identification of precast concrete building elements is realized by embedding RFID chips in the reinforcement.

Other important aspects investigated by subproject 4 are the optimal placement of so-called i-Points on the construction site, where the content of the RFID chip is read, and the development of technology for an immediate transmission of the captured data to the central construction site information system. Finally, methods for evaluating RFID data and updating the virtual representation of the construction site are being developed.

6 CONCLUSION

The paper has presented the ForBAU research cluster that aims at improving planning and management of construction sites. To this end, the research cluster develops a digital representation of the construction site, which integrates all data of the planning and the execution phase.

The presented research results include methods for an integration of 3D models originating from diverse sources, evaluation techniques for generating input data for earthwork simulations, approaches for simulating earthwork and bridge construction process, as well as methods for realizing an online tracking of the construction progress.

The research cluster has gained much attention from the German and the European construction industry and will continue its successful work.

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