VIRTUAL ROAD CONSTRUCTION – A CONCEPTUAL MODEL

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ABSTRACT: *Design, planning and logistics for road construction are increasingly performed using 3D models. These models can subsequently be used to guide machines directly on site. At present there is no direct integration of 3D design and production planning of the construction work, which limits use of the 3D models for optimization and real-time follow-up of mass haulage and machinery logistics.*

This paper describes a conceptual model of an industrial process for machine guided road construction projects where 3D design is integrated with production planning, enabling production visualization (4D) and real-time follow-up. The aim is to create an integrated working process to such an extent that redesign and replanning of activities and resources can actively be optimized, based on observations and data collected during the production.

KEYWORDS: *road construction, virtual construction, obsevational method.*

1 INTRODUCTION

Construction projects are normally executed using cost control rather than process control. Therefore, construction is focused on the management of the contractors and subcontractors individual activities by planning rather than understanding and control of the production process based on observations of the production rate. In many ways this prevents the implementation of new technologies and methods benefits and risks cannot be shared by all actors in the project. In road construction work, new opportunities have arisen due to the introduction of GPS, (Global Positioning System), guided earthmoving equipment. GPS can provide 3D positions anywhere on the earth to those with the proper receivers.

There is growing interest in modern road design and traffic route guidance. This is particularly true in larger projects such as highways, railroads, as well as construction site preparation for commercial industrial areas and buildings. To meet these project demands, contractors are turning to 3D Machine Control Systems.

This paper discusses the possibility for a more efficient design, planning and production process in machine guided road construction projects.

2 POINT OF DEPARTURE

2.1 Theoretical aspects

Most construction projects in Sweden are contracted using transactional oriented forms, such as design-bid-build contracts. The procurement process is often time and money consuming and gives seldom the actors in the design and construction phase incentives for innovations and cooperation in order to improve the project execution. Thus, the stakeholders often lack a common view on project targets and how the execution should be designed, an imperative condition to obtain a more efficient construction process, (Ballard & Howell). Furthermore the process design is based on principles that assume activities to be independent and sequential where the project management is focussed on cost control rather than execution, (Koskela and Howell). In reality activities are often interdependent and in fast-track projects the pressure increases the interaction between activities. As a result, stakeholders are unwilling to co-operate leading to unsatisfactory coordination, error prone information exchange between different stakeholders and sub-optimization causing large amounts of waste at the construction site (Josepson and Saukkoriipi 2005).

Another problem in civil engineering works, such as constructions of roads, dams and railways, is the risk involved in planning and execution of such projects where the ground conditions are relatively uncertain. The design, selection of machinery and hence the costs are strongly dependent on the field conditions for the project execution. Here, the possibility to modify the design and execution of the project as the conditions become more known can offer a way forward.

There are at least three theoretical frameworks that can be used to develop new methods and processes to make the design, planning and operations of machine-guided road construction projects more efficient:
- Influences from the lean production have inspired researcher in the field of contruction management to develop methods and tools that is known as lean constrution: "Managing construction under Lean is different from typical contemporary practice because; it has a clear set of objectives for the delivery process, is

aimed at maximizing performance for the customer at the overall project level, designs concurrently product and process, and applies production control throughout the life of the project", Howell (1999)

- In the field of geotechnical engineering uncertainties of field conditions have inspired researcher to propose an approach that is reffered to as the oservational method: "The Observational Method in ground engineering is a continuous, managed, integrated, process of design, construction control, monitoring and review that enables previously defined modifications to be incorporated during or after construction as appropriate. All these aspects have to be demonstrably robust. The objective is to achieve greater overall economy without compromising safety", Nicholson et al. (1999).
- Information management and especially on methods for virtual design and construction: Fischer and Kunz, (2004) defines Virtual Design and Construction as: "The use of multi-disciplinary performance models of design-construction projects, including the product (i.e. facilities), organization of the design-construction-operation team, and work processes, to support explicit and public business objectives", That is, one would like to analyse, simulate and predict the quality of the end product (e.g. a building, road, bridge etc) and the characteristics of the process to build and operate the product.

2.2 Technological aspects

In a machine guided project digital terrain models of road sections are transferred from the design to different types of equipment, such as rollers, graders, compactors, frontend loaders, haul trucks, etc. The downloaded data is used to guide the operator in performing the road construction work togehter with sensors and a positioning system, normally to a precision of 20 mm. The positioning is accomplished using Global Navigation Service System, (GNSS), optical instruments or laser. Since machine guided projects require that the design is made using 3D terrain models the foundation for creating a virtual platform is made. However, the 3D model is mainly used to create the digital data needed to automate surveying and to monitor and guide the earthmoving operations, not to improve the overall planning and execution of the project.

2.3 Process aspects

A typical Swedish road construction project (design-bid-built) suffers from the following disadvantages:

- Lack of information in the quotation phase; the cost estimation is based on uncertain quantities and schedules where previous experiences and offers from subcontractors are used to calculate the total costs for the project.
- Focus on procurement in the pre-planning phase; this phase focus on the amount of required resources, mainly from the purchasing point of view, very little time is spent on logistics and planning.
- No quantity infromation in production plans; the production plan is mainly based on main activities and milestones.

- Lack of control in the operation phase; the production plan is the base for the control. Since most production schedules lacks detail information of mass quantities, interim payments are often based on planned activities not on the actual circumstances.
- Lack of information for final financial regulation; the total amount of quantities are calculated including change orders that have been accepted during the course of the project. However, the the lack of information of quantities makes, e.g. changes in the project difficult to regulate.
- No systematic reuse of experience; lack of time and detailed project information makes it hard to evaluate the project efficieny.

3 A CONCEPTUAL MODEL

3.1 Introduction

The proposed process layout of machine guided road construction projects is based on a combination of the following ingrediants:

- An information deliver process based on a common geometrical model of the road for different applications used in the design and construction process, such as mass-optimization, estimation, planning, visualisation, generation of machine data and follow-up.
- An integrated design and construction process to support modifications to be incorporated as appropriate. Obstacles in contractual agreements between actors in the project must be removed.
- The management and control during construction is based on measured performance from real-time measures of the locations of machine-guided earthmoving equipment.

3.2 Information delivery process

The information delivery process is presented in figure 1. The process is divided in 5 main activities:

1. Tender preparation. Normally, a road adminstration/owner prepares the tendering of the road project by supplying information of the geotechnical conditions, profiles and estimated quantities of mass surpluses and deficits along the route. This information is the input to the contractor for the bid preparation process.
2. Bid preparation. To be able to estimate the cost the contractor needs to make a preliminary schedule and design for calculation of mass transports and use of resources. Today, tools are available for planning and optimization of the mass transportation, e.g. DynaRoad™. For example, changing the elevation of the proposed route can lead to a more economical mass balance and hence a lower total cost for the project. Therefore, this type of changes, or side offers, must be possible to propose if it can be shown that it will not lead to changes in functionality or safety.
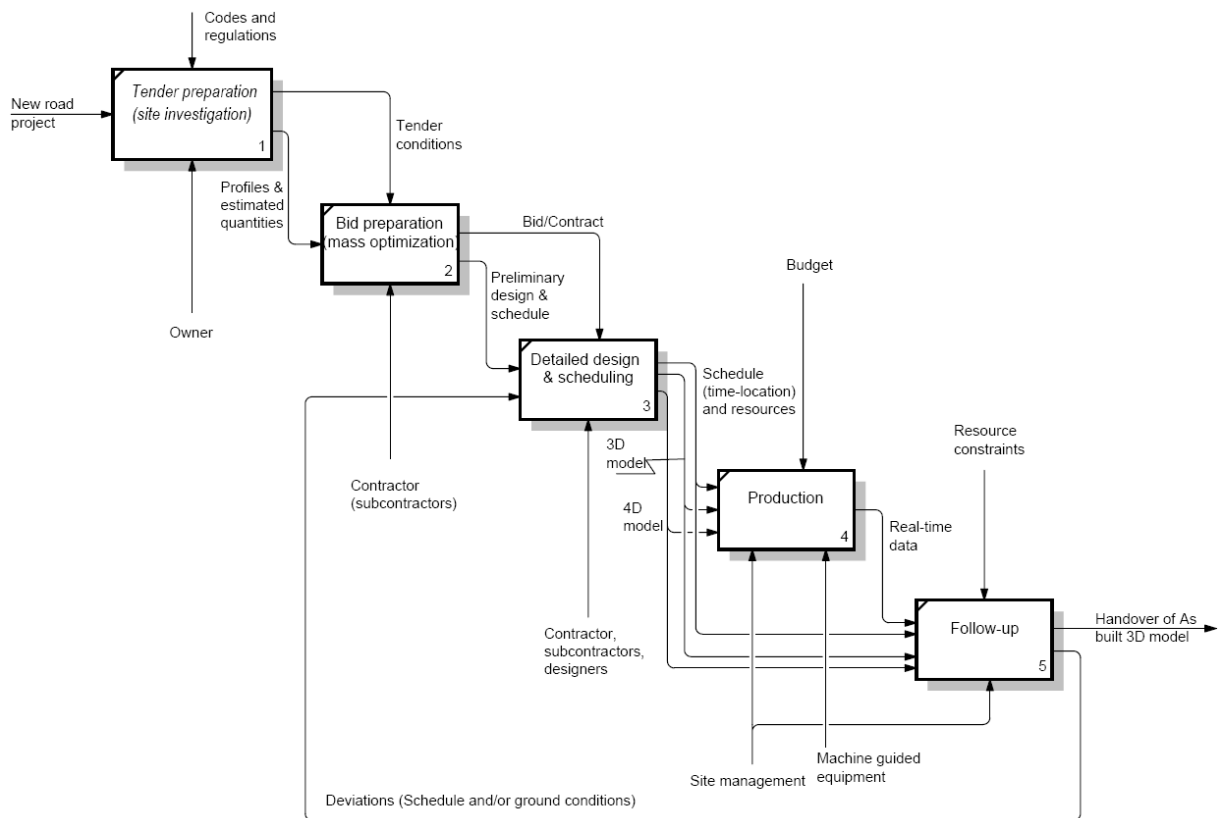
Figure 1. A conceptual information delivery process in a road construction project.

3. Detailed design and scheduling. In this stage the road different sectional layers is detailed. A 3D digital terrain model of the road project is prepared from which numerical data for the machine guiding can be extracted. Also, this model constitutes the base for the scheduling work and preparation of the 4D simulation model.

4. Production. The schedule and 4D model is used to communicate the intended work during the production phase. During this phase observations of the actual geotechnical conditions and the progress of construction may trigger changes in the design and schedule and it is important that such changes are not excluded by the contract.

5. Follow-up. In the field, these machine guided systems often have remote control functionality and can report back to control sofware often enabling the user enables the user to download data, run settings and monitor the operations, e.g. www.trimble.com. Based on this information action can be taken to alter the design and/or the schedule during production.

4 INTEGRATED DESIGN AND SCHEDULING BASED ON OBSERVATION

4.1 *Design*

Before earthmoving machine cuts the surface, there are considerable planning, surveying and design efforts that result in the project plan. The terrain model connects the design engineer, surveyor, and contractor into an integrated workflow using the same digital information to ensure accurate grading - and for site positioning during and after project completion. Several powerful software packages for geodesy and surveying are available today that includes designing, setting out, surveying, drawing, and reporting functions. Examples of Geodetic software packages used in Sweden are GEO, (SBG 2007), and Terramodel, (Trimble 2007). They are used to produce roadway designs, generate contours, calculate volumes and export road data (3D faces) to machine guided equipment.

4.2 *Scheduling*

The common technique to schedule a road construction process is the activity-based Critical Path Method (CPM). Based on calculating how long it takes to complete essential activities and analyzing how those activities interrelate, CPM provides a visual and mathematical technique to plan, analyse, schedule and monitor construction projects.

The main concept of the method is that a limited set of activities control the entire project. These activities together are called the critical path. If the activities on this critical path can be identified and managed properly, the fate of the entire project can be controlled. The final network is often presented in a bar chart known as Gantt chart that describes the proposed schedule of the project. The customary approach is to prepare a master schedule of this kind that is used as a basis for plans of more specific nature, like more detailed short-term plans (Koskela 1999). These CPM schedules are in many cases discipline oriented and do not explicitly consider the spatial layout and interaction between trades.
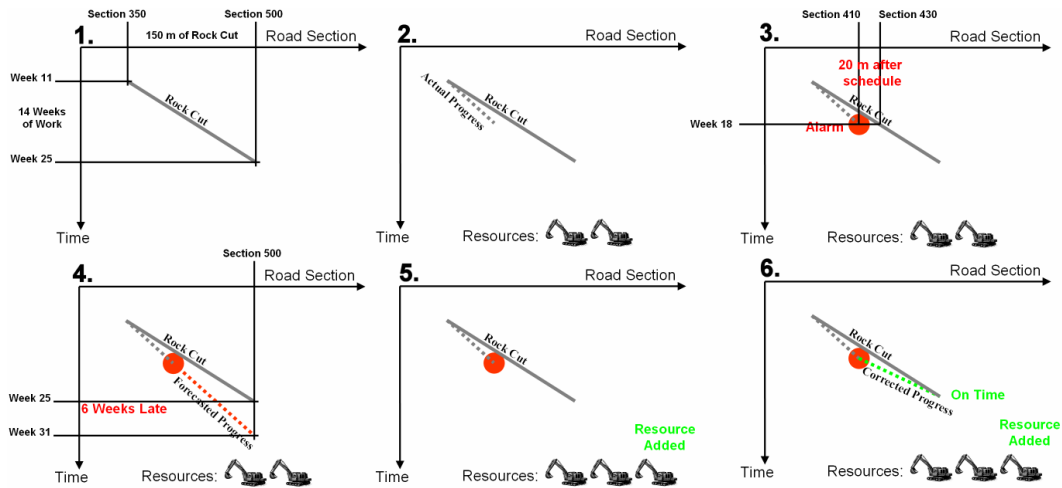
Figure 2. An example of the use of Time-Location technique in road construction, adapted after DynaRoad (2007).

Time-location scheduling is a visual scheduling technique that allows the planner to explicitly account for flow of a project (Seppänen 2004). The practical use in construction has been limited, mainly due to the strong tradition of activity-based planning and the absence of software packages that support location-based planning. Research on location-based scheduling method has been carried out since the 1940s and variations of the method appear in literature under different names, such as 'Line-of-Balance', 'Flowline', 'Construction Planning Technique', 'Time-Location Matrix Model', 'Time-Space Scheduling Method', 'Disturbance Scheduling', etc. (e.g. Harris 1998, Kenley 2004). The Line of Balance method (LoB) uses lines in diagrams to represent different types of work performed by various construction crews that work on specific locations in a project. In a road construction projects the spatial dimension is the distance along the planned route, the road section. Figure 2 shows how the method can be used to plan and control the progress of a 150 m long rock cut.

The essential steps are as follows:

1. Given the location for the work between road section 350 and 500, the amount of mass quantities and the rate of production for the selected resources, the time of production can be estimated to finish week 25 if the works start at week 11.
2. The actual progress of the rock cut is shown as a dashed line
3. On week 18 an alarm is triggered since the work is 20 m after schedule.
4. A forecast show that if the current progress rate is retained this part of the road section will be 6 weeks late.
5. The site management decide to add resources to speed up the work
6. This will put the project on time

This simple example illustrates the visual strength of the Time-location method compared to Gannt charts. There are at least two commercially available software packages on the market, DynaRoad, (DynaRoad 2007) and Tilos (Asta Development 2007). DynaRoad is specialized on road construction and have support for calculating mass balance and haul distances, evaluating costs of different design and planning alternatives. Also the sofware can create optimized schedules and have support for monitoring of actual hauls and control of project progress.

4.3 Production simulation, 4D CAD

4D CAD models are created by linking building components from 3D CAD models with activities that follow from CPM or Time-Location schedules, e.g. (Koh and Fischer 2000, Jongeling 2006). The 4D CAD model provides the user with a clear and direct picture of the schedule intent and helps to quickly and clearly communicate this schedule to different stakeholders in a project. 4D CAD models allow project participants to simulate and analyze what-if scenarios before commencing work execution on site (Fischer and Kunz 2004). Based on Japanese experiences, (Nakagawa 2005) illustrates the importance of visualization for the maintenance of a synchronized and paced work-flow and for the implementation of Lean Thinking in construction. Construction site workers tend to focus on their own tasks and therefore become indifferent to other related activities which often create waste in the form of rework and work out-of-sequence, particularly in projects with a large number of activities and crews. Proper visualization of overall project progress is encouraging workers to improve their own work and the coordination with other work crews, which facilitates work-flow while waste is reduced. Common for projects using 4D CAD is visualization of design decisions and improved communication of these decisions in the design and construction phase (Woksepp and Olofsson 2006, Jongeling 2006). Most of today's 4D CAD models are used to communicate schedule intent, often at a macro-level in a project, using building components from a 3D CAD model that are linked to activities that follow from activity-based scheduling methods. However, there are a number of research initiatives that aim to extend the use 4D models beyond this use (Akbas 2004, Jongeling 2006). Figure 3 shows a first attempt to visualize a road construction project using the Ceco 4D viewer, (Ceco 2007).
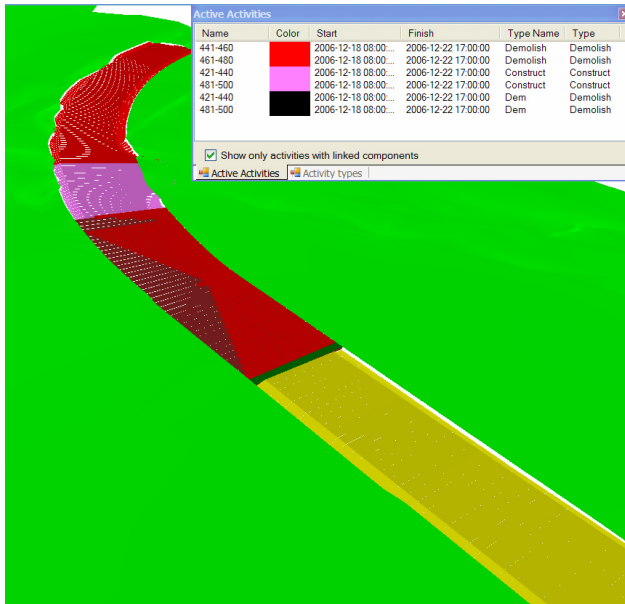
Figure 3. A 4D CAD view showing different scheduled activities in a hypothetical road project.

4.4 *Observational control*

Information observed during construction can be used to optimise the remaining part of the construction or structure. This procedure is normally called the Observational Method in geotechnical engineering, (Nicholson et al 1999). There are two types of observational data in a road project that can alter the course of action in production phase; geotechnical and progress information.

The Swedish Road Administrations guidelines, so called ATB Väg, are normally used for the design of roads in Sweden. However, these guidelines do not take into account the actual conditions of the underground and the supporting bearing layers. This leads to wrong design solutions due to lack of detailed geotechnical information. SwePave, (Peab 2007), is an example of a developed observational method for the design of the road support bearing layer. Using laboratory test and proven field test during construction, the material characteristics in the support layers is optimized. Also, soil stabilization methods can be applied.

Navon et al (2004) presented a model for automated control of earthmoving project management. The model is based on the concept of automatically measuring the performance, by measuring indirect parameters—in this case, locations. The machine locations are an indirect measure of control data such as productivity (or progress) and materials consumption. The locations can be measured, at regular time intervals, using the GNSS machine guiding system.

These are examples of observational control of the design and the progress in a road construction project. Deviation from plan can be dynamically adjusted by changing the design and/or the schedule during production. However, any changes must be easy to implement using an integrated flow of information, through (re) design, (re) planning, (re) scheduling and update of machine control data.

4.5 *Information integration*

Rebolj (1998) described an integrated information system that intended to support an iterative road design and construction process. Since, then the development and use of machine guiding in road construction projects have laid the foundation for the realization of such a system. The first step of information integration is to enable the information flow between the different applications used in the process. Figure 4 shows the information flow in an integrated detailed design and scheduling process that can be triggered from the initial layout of the road or a change order during the contruction work.

The steps are as follows:

1. The detailed design starts with breaking down the initial layout into locations in the design software. In case of a change order this step can be omitted.
2. The different load bearing layers is designed according to the assumed (initial) or actual (change order) geotechnical conditions.
3. Information of the sectional geometries of the terrain and load bearing layers are collected for use in the scheduling process and export of machine data.
4. Mass optimisation and of cut and fills and a graphical 3D model is created from the sectional data.
5. (Re) sheduling of activities and mass haul transports are made using Time-Location technique.
6. The (changed) production plan is visualised (4D) by combining the 3D model with the schedule.
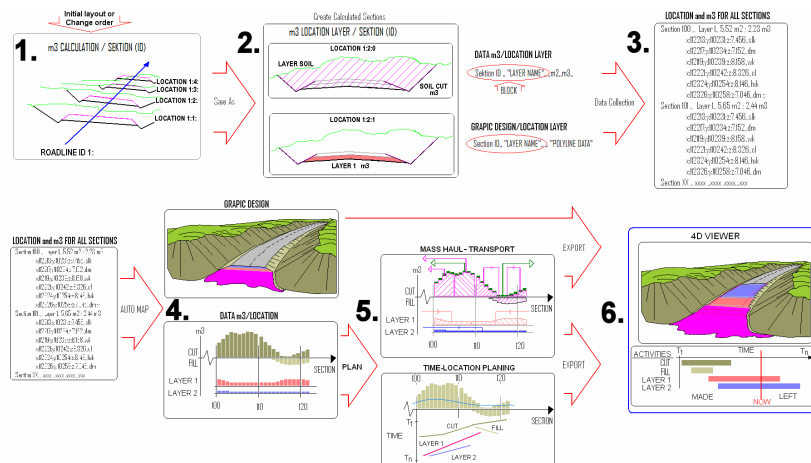

Figure 4. An integrated information flow between different applications in the detailed design and scheduling process.

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The locations of the guided machines can be used to show the production progress in the Time-Location schedule and/or the 4D viewer. In case of a schedule change only step 5 and 6 needs to be performed. A redesign involves step 2-6 for the sections affected by the change.

5 DISCUSSION AND CONCLUSIONS

This paper has presented a hypothetical working process of the design, planning and execution of machine guided road construction project based on an integrated information flow between different applications used in a machine guided projects. The concept is based on the (3D) terrain models needed to execute machine guided road construction projects. Three methods or philosophies are used in order to create a more efficient design and contruction process; the Observational Method, Lean Construction and methods applied in Virtual Design and Construction. The proposed design and planning process is based on existing technologies and software availaible on the market. However, the information flow (export/import of data) between these applications needs to be developed.

The suggested process as a whole needs to be proven in real road construction projects. The suggested methods for control e.g. monitor of machine locations must also be tested and refined. Is it possible to get geotechnical information of the ground conditions directly from reported machine data? Can mass quantities and transports be traced more accurately using other measures than locations?

When these issues been resolved and proven in practice the natural next step would be to implement a central information server solution, a "Road Information Model", as proposed by Rebolj, (1998).

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