METHODS FOR AUTOMATED CIVIL CONSTRUCTION PRODUCTION CONTROL

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ABSTRACT

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The goal of this study is to understand the background and current state of the production control in an automated civil construction jobsite. The study is used as a basis for a production control requirements document. The topics include examination of machine control systems in the role of work implementation, BIM process for product model and production control and management in general.

The machine control systems improve the efficiency of working by 30-100%. The improvement is based on a direct real-time access to the production model. The operator does not need stakeouts from the Surveyor and needs fewer instructions from the Supervisor. The biggest savings on effort are calculated with fully automated motor graders that can produce the final layer to the accuracy requirement of five millimeters. This is not a simple task to achieve without the machine control system.

The BIM process is coming to civil construction from building construction where the process has reached the level of requirement within the most advanced product owners. The BIM cannot be adapted straight from the building construction to civil construction. The biggest obstacle is the difference of the product model itself that cannot be modeled and interoperated by using the same techniques. Simply put, the IFC standard in buildings and other structures is based on solids, like Lego blocks. In civil construction the product could be continuous, kilometers long geometry full of mathematical dependencies to its construction layers. This is not clever to build by Lego blocks; the continuous string line model would probably lead to a better result.

Before production control is possible there are some perquisites. The production needs a plan and the realized status of the work needs to be gathered. Control is possible when deviations between the plan and realized status are calculated. The work in civil construction is not repetitive in a single location, like in the manufacturing industries. There are methods, like location-based management system and time-distance chart that allow controlling of the moving fleet better than standard project management tools. The methodologies are based on principles and concepts. The civil construction industry has started to use principles of Lean thinking that is made popular by Toyota. Lean focuses on eliminating the waste. Everything that does not add value for the end customer is waste. Another part of the modern management methods is the benchmarking and active improvement of processes by learning. Also a brief look into production control in other industries, mechanical engineering and building construction is done.

Key words: machine control production model

TIIVISTELMÄ

Tampereen Ammattikorkeakoulu
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VISA HOKKANEN:
Menetelmät maanrakennusalan tuotannonohjaukseen

Tutkintotyö 78 sivua
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Työn tarkoituksena on ymmärtää maanrakennusalan tämänhetkinen tila tuotannonohjauksen suhteen. Työtä käytetään tuotannonohjausjärjestelmän vaatimusmäärittelydokumentin laatimiseen. Tuotannonohjaukseen uskotaan liittyvän seuraavat asiat: Koneohjaus toteuttavana vaiheena, BIM tietomalli ohjaavana tekijänä ja tuotannonohjausmenetelmät yleisesti.

Koneohjauksella on mitattu saavutettavan 30-100% työtehon lisäys. Tehonlisäys perustuu siihen, että koneen kuljettaja voi toimia itsenäisesti ilman erillistä mittamiehen tekemää maastoonmerkintää ja voi jatkaa työtä itsenäisesti eteenpäin, koska työmaasuunnitelma on näkyvissä koneohjauslaitteistossa. Huimimmat edut saadaan aikaan automaattiohjatulla tiehöylällä, jossa terää ohjataan tuotantomallin mukaisesti. Laatuvaatimuksen mukainen viiden millimetrin tarkkuus lopulliselle pinnalle on erittäin vaikea saavuttaa ilman ohjausjärjestelmää.

BIM toimintamalli on tulossa kovaa vauhtia maanrakennuspuolelle. Syy tähän löytyy talonrakennuspuolelta, jossa valistuneimmat omistajat vaativat BIM prosessin käyttöä kaikissa omistajalle toteutettavissa hankkeissa. Tekniikat eivät ole suoraan yhteensopivia, johtuen lähinnä eri toimialojen mallinnustarpeista. Avoin IFC formaatti mallintaa taloa tai siltaa solideilla. IFC ei tunne jatkuvan geometrian käsitettä, joka on perustekniikkaa mallinnettaessa esimerkiksi moottoritietä. Väylägeometrian lisäksi maanrakennuspuolen tietomallissa on matemaattisia riippuvuuksia väylän rakenteisiin. IFC mallin solidin voi ajatella esim. Legopalikkana, kun taas väylää olisi helpompi kuvata esimerkiksi murtoviivajoukkoina.

Ennen kuin tuotannonohjaus on mahdollista, tarvitaan suunnitelma, toteuma ja näiden vertailu. Työ maanrakennuksessa etenee kokoajan ja toistuvaa työtä samoilla parametreilla ei käytännössä tehdä, kuten esimerkiksi valmistavassa teollisuudessa. Maanrakennukseen on kehitetty omia menetelmiä, kuten sijainti-perustainen menetelmä ja ns. tieaika kaavio, joiden avulla työkoneryhmiä voidaan ohjata tehokkaammin. Kaikki menetelmät perustuvat periaatteisiin ja käsitteisiin. Maanrakennusyrityksissä on omaksuttu Toyotan tutuksi tekemä Lean ajattelu. Leanin periaatteisiin kuuluu hukan vähentäminen. Hukalla tarkoitetaan kaikkea toimintaa, joka ei lisää arvoa asiakkaalle, tässä tapauksessa tuotteen omistajalle. Toinen periaate on jatkuva prosessien tehostaminen, suunniteltujen tehtävien toteuman seuraaminen ja epäonnistumisten arviointi. Lopuksi tutkitaan myös tuotannonohjaukseen ja yhteistyöhön liittyviä asioita mekaniikkasuunnittelun ja talonrakennuksen näkökulmasta.

Avainsanat: työkoneohjaus työkoneautomaatio tuotannonohjaus

FOREWORD

This study is done for the company Novatron Oy. The Novatron Oy designs, manufactures and supplies Machine Control Systems and offers services to the related business. The writer works in the position of Research and Development Manager for Novatron at the time written. A lot of information in this document is gathered during the years 2002-2012 from different experts in the Civil Construction industry.

The motivation to write the thesis about Production Control in Civil Construction is coming directly from the work. The Civil Construction industry in general is wasting a lot of effort, time and money when working by using the old methods. Normally the first step in the Civil Construction process enhancing is the utilization of the machine automation. The next drastic change involves the rebuilding of the complete product life cycle process. The more intelligent data from the design would enable more efficient management, planning and production control for the civil construction jobsite. A good product for the total process controlling would strengthen the position of Novatron Oy as a machine automation supplier.

The completion of this study would not have been possible without connections to the industrial and research partners. I would like to thank Adjunct Professor Rauno Heikkilä from University of Oulu for invitations in to the interesting research projects and workshops, Pasi Nurminen and Mika Jaakkola from Destia for technical review and technological challenge during the years, Senior Lecturer Pekka Pöyry from TAMK for his flexibility and Lotta Huhtiniemi for guidance in written English. Thanks to all my colleagues in Novatron for the inspiring environment and especially Jukka Tervahauta for a chance to get to know this interesting business. Finally, thanks go to my wife Minna for encouraging to a lifelong learning.

Tampere, December 2012

Visa Hokkanen

CONTENTS

GLOSSARY

TAMK	Tampere University of Applied Sciences
SaaS	Software as a Service
Stake out	Marking pole on the field that is measured by surveyor.
Surveyor	An expert in the civil construction jobsite having knowledge to production models and measurement techniques.
Operator	Work machine’s driver.
ISARC	International Symposium on Automation and Robotics in Construction and Mining
ICT	Information and Communications Technology
Retrofit	System installation that does not take place during the original manufacture of the machine.
CAN	Controller Area Network
HMI	Human machine interface
GPS	Global positioning System
Civil Engineering	Design, construction and maintenance of the physical and naturally built environment
CAD	Computer Aided Design
GPS	Global Positioning System
GLONASS	Globalnaya Navigatsionnaya Sputnikovaya Sistema. Russian satellite navigation system.
GNSS	Global Satellite Navigation System
RTK	Real-Time Kinematic
WGS84	World Geodetic System 1984
ECEF	Earth-centered Earth-fixed
ppm	Parts Per Million
RTCM	Radio Technical Commission for Maritime Services
CMR	Compact Message Record
UHF	Ultra High Frequency
NTRIP	Network Transportation of RTCM message via Internet Protocol
HTML	Hypertext Transfer Protocol
API	Application Programming Interface

GPU	Graphics Processing Unit
GUI	Graphical User Interface
BIM	Building Information Modeling
DTM	Digital Terrain Model
TIN	Triangulated Irregular Network
DXF	Data exchange format
LandXML	Open data exchange format for Civil Engineering purposes based on XML syntax
Inframodel	Definition how LandXML should be used
GIS	Geographic Information System
OGC	Open Geospatial Consortium
buildingSMART (bS)	Organization supporting open BIM through the life cycle
bS ITM/IUG	buildingSMART International Technical Management Committee / International User Group
MVD	Model View Definitions
ROI	Return on Investment
IGES	Initial Graphics Exchange Specification
CAM	Computer-aided Manufacturing
PDM	Product Data Management
TPS	Toyota Production System
UID	Unique Identification Number
PPC	Percent Plan Complete

1 INTRODUCTION

The change of the workflow from drafting-centric to BIM in civil construction projects together with increasing utilization of the machine control systems in the jobsite change the daily life of the stakeholders of the project. Especially the routines and processes of the project management in the jobsite change and new tools are needed for production control. (Jaakkola, 2010)

Production control and product life cycle management systems are widely used in other industries where the complete assembly consists of rigid parts. In infrastructure industry only structures like buildings and bridges and accessories, such as light poles share the same analogy. When the product model is a continuous, curving geometry and involves production materials such as rock and gravel, the production control methods are very different by nature. Models and tools used in other industries cannot be directly adopted into the civil construction jobsites.

Work productivity needs to increase continuously; the justification for this can be anything between smaller environmental impacts to the profit of a company. Therefore novel production control and product life cycle management systems are needed for civil construction business. The extending use of cloud services, software as a service business and increasing performance of mobile platforms have made a dramatic change to the way, how people communicate and utilize new technologies in their personal and professional life. This is a great enabler for the SaaS business for the civil construction projects.

This work examines the current automated production process from the perspective of machine control, product modelling and jobsite management. These topics are chosen to help defining the requirements for the production control system development.

2 RESEARCH METHOD

The purpose of this study is to understand the interfaces, stakeholders and workflow from design to production and back to quality assurance and maintenance in civil construction jobsite.

2.1. Research problems and goals

The problem is to find a more efficient way for jobsite stakeholders to perform their daily work. The goal of this paper is to gather the information for a requirement document for a system that enhances the production phase of the civil construction project. The generation of the requirements requires a holistic understanding of the civil construction business. For gathering the understanding the following topics are examined: civil construction machinery and automation, civil construction jobsites and existing production control systems.

2.2. Related research

The existing research result could be divided in to two groups. The first group of papers concentrates on enhancing the processes of a company by utilizing modern technology, such as building information modeling and machine control. This information is very helpful for finding the key elements for better processes and for the elimination of the bottlenecks of the current process. The second group includes scientific papers focusing on BIM, machine control and construction processes and management. The related research is referred directly in the chapters below in corresponding topic.

Overall, there are not many published papers directly addressing the issue of civil construction jobsite production control. The best matching documents are “Virtual Road Construction – A Conceptual View” written by Söderström and Olofsson in Luleå University of Technology and “Real-time control of mass hauling in a road construction project” written by Halme in the University of Oulu. (Soderstrom & Olofsson, 2007; Halme, 2008)

3 CIVIL CONSTRUCTION MACHINERY AND AUTOMATION

Automation in construction means the utilization of machine automation and ICT in purpose of enhancing the process or task in a construction site. The simplest level of automation allows operator of the machine to implement a task faster, more precisely and typically more affordably. In bigger scale, automation means enhancing the work of the complete machine fleet by using new processes enabled by modern ICT.

3.1. Modern autonomy level in different machines

One way to determine the automation level is to use the count of axis of freedom for measurement operation. This is a common way for machine automation suppliers to explain the difference between the systems. 1D system measures tool position in level plane and 3D system knows the actual 3D coordinate for the tool. 2D system is not so trivial to determine. Other suppliers count the boom line distance measurement for second dimension and others require a slew sensor for machine orientation determination to achieve the 2D level. Another way to determine the autonomy level of the application is presented by Kilpeläinen et al. (Table 1).

TABLE 1. Autonomy levels in construction machine. Table modified (Kilpeläinen et al., 2004, 16).

Level	Automation level	Features
1	Operator guidance	The machine is operated manually while control system guides the operator of a machine.
2	Coordinated control	The machine controls the movements of the machine according to commands supplied in Cartesian system by the operator.
3	Partly automated	Some parts of the machine are moving automatically according to target levels supplied by the operator.
4	Fully automated	The work is implemented with full automatic control in operator's surveillance.

5	Autonomic system	The work is implemented automatically without surveillance.

Modern automated jobsite includes machines with automation level 1-4. The reasonable level of automation depends on the type of the work machine. The level one is sufficient for excavator while level four is most suitable for the motor grader. Other common civil construction work machines are bulldozers with any autonomy level from one to four and wheel loaders with level one. The asphalt paver machine automation is usually done in level three and compaction machines in level one. Table 2 below describes different machines and their autonomy level with typical count of axis of freedom.

TABLE 2. The autonomy level of construction machinery in a modern jobsite. Pictures in authority of Moba AG (Moba).

Machine picture and name	**Tasks**	**Level of autonomy**	**Axis of freedom**
 Compaction machine	Compaction of pavement and fine gravel layers. Ensure the quality of built layers by right amount of passes. Pavement temperature monitoring.	1	3
 Asphalt paver	Control system used to ensure smooth surface in the pavement.	2-3	1
 Motor grader	Finishing fine gravel layer with accuracy of plus minus 5mm.	4	3

 Bulldozer	Fill and mass haul operations by rock and gravel.	1-4	3
 Excavator	A multi-purpose machine. Loading of soil cut to the truck. Constructing the embankments and other construction layers down to accuracy requirement of 20mm.	1	3
 Surface-top drill	Drilling hole patterns for rock explosion purposes.	1	3

The automation level for each machine depends on the accuracy requirement and challenge of the implemented task. In a road construction site accuracy requirement increases layer by layer from cut to pavement. The difficulty level of the task for a machine can vary greatly in civil construction jobsite. It is simpler to automate the machine that screeds material than automate the loading of a truck or dumper. Most of the machine control systems are so called retrofit systems; they are installed after the work machine is sold to the customer.

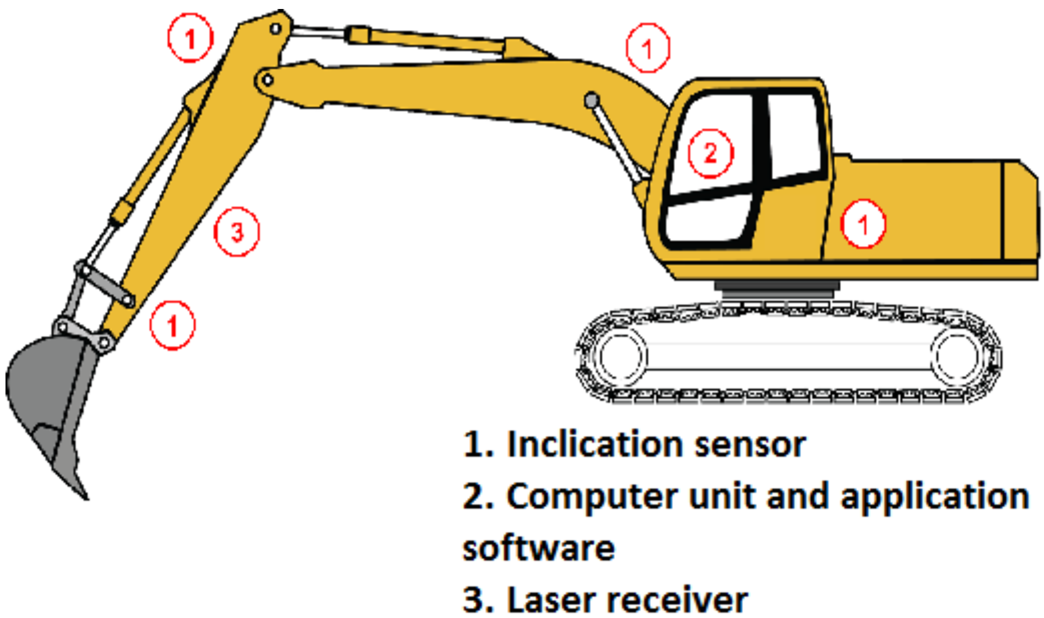
The four biggest Machine Control system suppliers are Trimble, Topcon, Leica Geosystems and Moba AG. Moba AG is very strong in paving applications and in OEM business while the three other players have very strong background in measurement technologies such as GNSS and total stations. Novatron Oy's Machine Control guidance products are distributed via Moba AG. All four have quite a similar product basket in the matter of machine control (Trimble, Topcon, Moba, Novatron).

The Machine Control System introduction is divided into five chapters below:

- The inner state of the machine. This chapter explains the technologies used for measuring the tool position in respect to the machine frame. This leads to automation level 1 in 2 dimensions.
- Hydraulic control. Controlling the tool by sensors and controller unit. This chapter explains the method to reach automation level 3 in a screed type of work machine.
- Positioning systems. GNSS and total station technologies. Allows 3D applications.
- Processing.
- Data exchange.

3.2. Inner-state of the machine

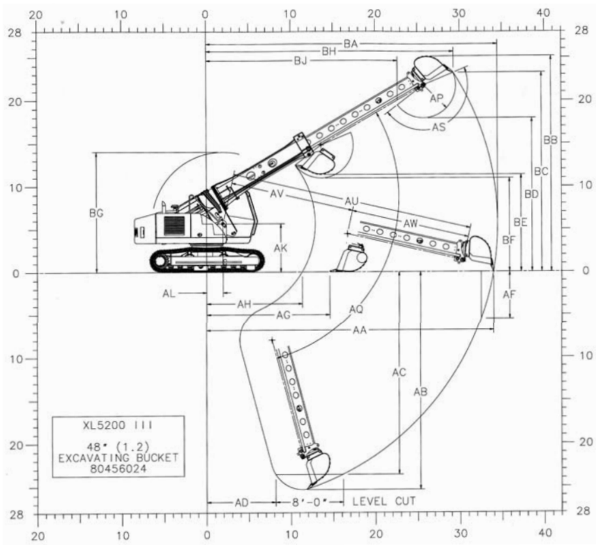
Inner state measurement of the work machine is the base for all advanced machine control applications. The inner state is usually measured from position reference to the tool location. For example in excavator application the position reference could be located in the rotation centre of the machine. The tool in the excavator is typically a bucket or other accessory equipment that is located at the end of the boom chain (Picture 1).



PICTURE 1. Excavator machine control application

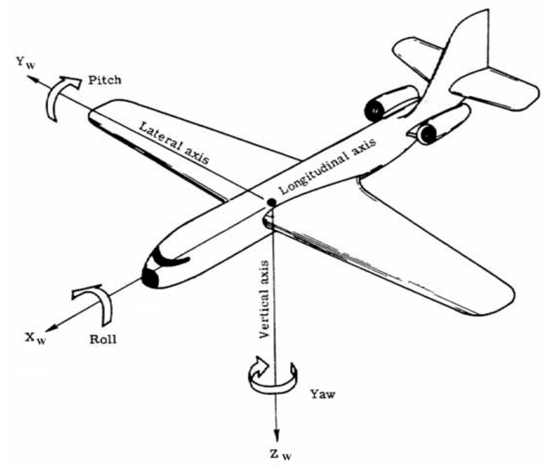
The most common inner-state sensor is an inclination sensor that measures the inclination of one part of the machine in a chain from tool to position reference. Such parts in the chain are boom, tool or machine body. When the machine control system is installed, its dimensions and inclination sensor orientations are calibrated and stored into its memory. This installation data is used together with an online sensor output to solve the real time inner-state of the machine.

The inclination sensors that are based on gravity measurements are not sufficient to solve all inner-state measurement needs. The problematic places for inclination sensors are telescopic booms where the dimension of the part can change in real-time. The other sensing technologies, such as a string-wire encoder, an ultrasonic sound or radio wave becomes handy.



PICTURE 2. Telescopic boom.

Another problem comes up with parts of the machine that rotate around the gravitation axis of Earth. The orientation of the part cannot be measured in respect to acceleration caused by gravitation of Earth (Yaw angle, Picture 3). In this case using an encoder or gyroscope could solve the relative orientation. The solutions for absolute orientation require either 3D positioning or heading sensors utilizing the magnetic field of the Earth or GPS heading.



PICTURE 3. Roll, Pitch and Yaw-angles.

The inner-state sensors are typically embedded systems including integrated circuits like a micro-controller, FPGA and DSP for calculation and communication. Communication to the controller unit or HMI is usually done over a CAN bus. A CAN bus is a field bus designed for vehicles (CAN bus). There are competing higher layer protocols in CAN but the most common in the area of machine automation is CANopen. The use of CAN bus for machine control is easy to justify:

- The protocol has very good redundancy for data
- The maximum bus cable length is sufficient with required data speed
- The CAN bus technology is widely adopted by car manufacturers and therefore the availability of low cost micro-controller chips with integrated CAN functionality is good.

3.3. Hydraulic control

When inner state of the machine is solved it is possible to increase its automation level by controlling the hydraulics of the machine. The hydraulic control technique is well adopted for the levelling or screed type of machines, such as motor grader and bulldozer. The common solution is to use a control loop where inner-state sensors are used for sensing the current state of a part and outer logic to determine the current set point or target level. The control loop drives the valves that control the cylinder of the machine. The principle can be seen in figure 1 below.

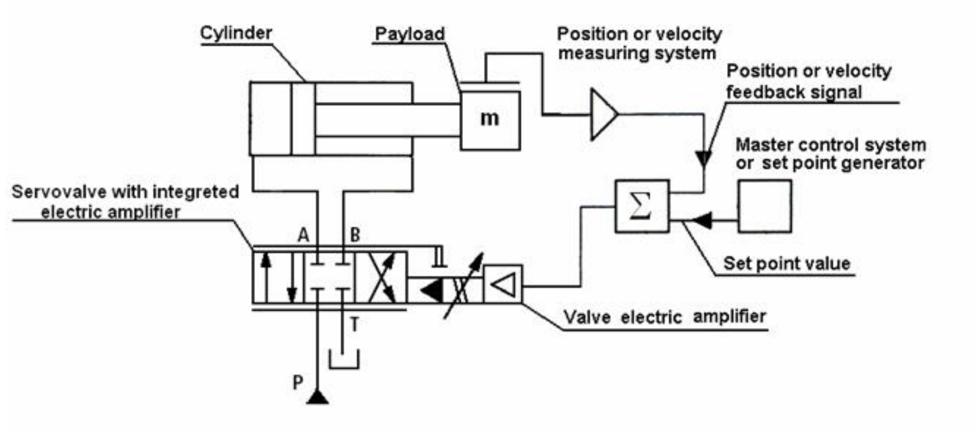


FIGURE 1. Hydraulic control loop (Borowin et al., 2004)

There are many different methods to create the control logic to the control loop. One option is a proportional-integral-derivative controller. The text describing the principle of a PID in Wikipedia:

> A proportional–integral–derivative controller (PID controller) is a generic control loop feedback mechanism (controller) widely used in industrial control systems – a PID is the most commonly used feedback controller. A PID controller calculates an "error" value as the difference between a measured process variable and a desired setpoint. The controller attempts to minimize the error by adjusting the process control inputs.
>
> The PID controller calculation (algorithm) involves three separate constant parameters, and is accordingly sometimes called three-term control: the proportional, the integral and derivative values, denoted P, I, and D. Heuristically, these values can be interpreted in terms of time: P depends on the present error, I on the accumulation of past errors, and D is a prediction of future errors, based on current rate of change. The weighted sum of these three actions is used to adjust the process via a control element such as the position of a control valve, or the power supplied to a heating element. (PID)

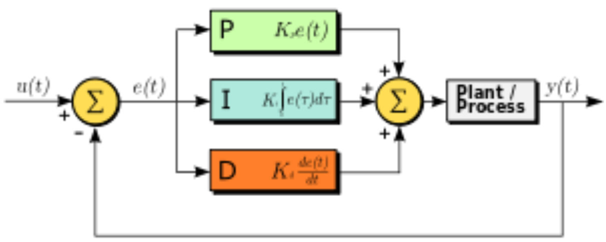


FIGURE 2. A block diagram of a PID controller (PID)

The most common application for a control loop in a construction machine is a blade angle control according to a setpoint value. Normally the cross slope of the road is known and could be set by the operator to the value of 3% (set point). In the case of the motor grader the following inner state sensors are needed to calculate the real time cross slope of the tool (measured process variable):

- Pitch and roll angles of the machine body
- Blade rotation angle sensor
- Blade pitch and roll sensor

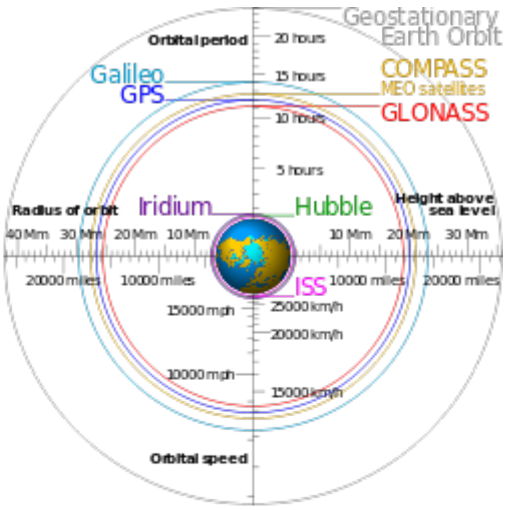
According to these variables the PID can calculate the error value and correct the process.

3.4. 3D positioning sensors

3D position sensors are required to enable features like fleet management and the utilization of production model in machine control system. For positioning of humans or vehicles for management purposes, the accuracy of ten meters is fully sufficient. Integrated GPS receivers in a modern smart-phone or a tablet can easily reach this accuracy. When positioning is required for a proximity alarm or machine guidance the accuracy requirement is usually below one meter.

3.4.1 Satellite navigation

Satellite navigation is the most affordable way to reach centimetre level accuracy at the time written. There are two fully operational satellite navigation systems running in 2012: GPS that has been available for all civilians from the year 2000 and a Russian system GLONASS that has recovered the full global constellation in 2011. There are two other satellite navigation systems aiming for global coverage, European Galileo and Chinese Compass. The non-system specific term for satellite navigation is GNSS. (GPS; GLONASS; Real-time kinematic)

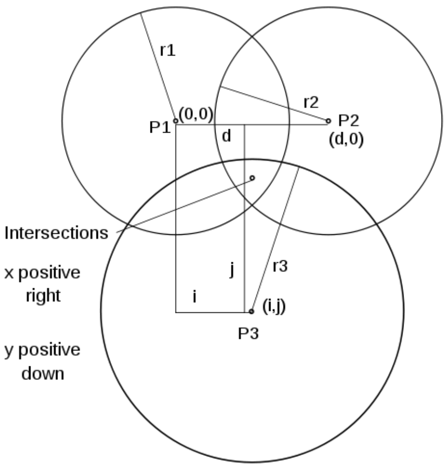


PICTURE 4. Orbit of the Earth and satellite navigation systems (GPS)

Satellite navigation concept is written in Wikipedia as follows:

> A GPS receiver calculates its position by precisely timing the signals sent by GPS satellites high above the Earth. Each satellite continually transmits messages that include
> - The time the message was transmitted
> - Satellite position at time of message transmission
>
> The receiver uses the messages it receives to determine the transit time of each message and computes the distance to each satellite using the speed of light. Each of these distances and satellites' locations define a sphere. The receiver is on the surface of each of these spheres when the distances and the satellites' locations are correct. These distances and satellites' locations are used to compute the location of the receiver using the navigation equations. (GPS)

All satellite systems follow the same basic concept: the calculation of distances between each satellite and the positioning receiver and solving the position by trilateration (picture 5). Trilateration with a carrier phase GNSS measurement requires a sight to minimum of five satellites. Mixing satellites from different systems is not very trivial. This is due to incompatibility of the navigation systems. The biggest challenge between GPS and GLONASS is the different channel access method. The GPS system transmits the data in CDMA (Code Division Multiple Access) signal while GLONASS is using FDMA (Frequency Division Multiple Access) signal. Synchronizing these two systems has been quite challenging for the GNSS technology suppliers. The latest generation of the GLONASS satellites (2011-2012) have also support for CDMA test signals. (GLONASS)



PICTURE 5. Trilateration (Trilateration)

3.4.2 Real-time Kinematic

The most precise navigation technique for real-time positioning is a Real-time kinematic (RTK). The system utilizes a stationary reference station that is a similar receiver to a dynamic rover receiver. Both receiver units use the carrier phase measurement of the satellite navigation system. The reference station transmits real-time corrections to the rover unit. The rover unit assumes that the error measured by the reference station applies also to the current measurement in the rover side. In practice the most common machine control applications utilizes the static reference stations with radio link that communicates the correction messages to the rover.

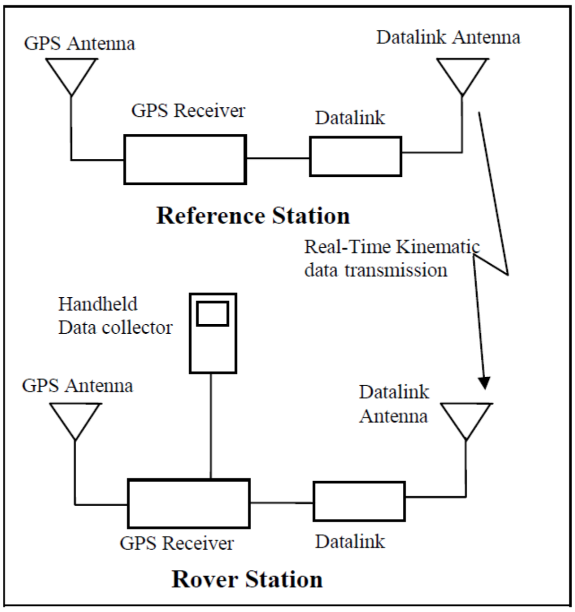


FIGURE 3. RTK correction data transmission (Talbot, 1996)

The radio technology depends on local legislation and authorities. In northern Europe the most common solution is UHF radio with a capability of data speed of 38400 bit/s (Satel, 2010, 76). This is sufficient for GNSS correctors today in any format in rate of 1Hz that is sufficient to reach ppm accuracy readings of the most common GNSS receiver manufacturers. However, the completion of Galileo and Compass systems tests the limit of a UHF bearer channel.

Another practical solution for a bearer is the Internet. The required data rate can be easily achieved with modern mobile devices. The protocol for streaming correction messages from the Internet is called Ntrip. This protocol introduces the login procedure, service discovery and streaming of correction messages in HTTP (Ntrip).

The maximum distance between the reference station and the rover is about forty kilometres. The accuracy of the positioning result depends on the distance between the reference station and the rover. Typically this error is horizontally 1 cm + 0.5ppm and vertically 2 cm + 1ppm. This means that the variance in measurement increases by 0.5mm horizontally and 1 millimetre vertically by every one-kilometre distance difference between the reference station and the rover in addition to other errors that are counted to static accuracy reading. The maximum allowed distance between the reference station and the rover depends on the accuracy requirement of the application. (Navcom)

Other error sources for GNSS measurement includes:

- Multipath: multiple received messages from a single satellite vehicle to the rover due to the reflection of signals from the machine rooftop, walls and similar obstacles.
- Satellite geometry: Either the rover or the reference station could be located so that geometry for satellite locations is not well distributed and therefore trilateration is not precise enough. A common quality parameter for this is the dilution of precision.
- Atmosphere: The atmosphere causes delays on radio signals that make distance measurement more imprecise. The most of this error is tackled by the concept of nearby reference station. The atmosphere error is not constant and requires modelling for complete compensation.

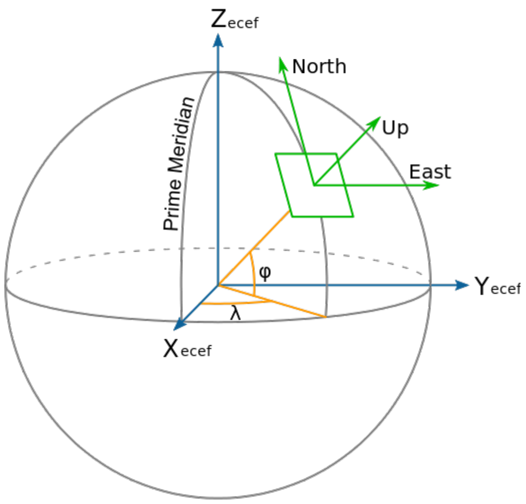
There are different correction message protocols that are used for RTK. Most receiver manufacturers have their own proprietary format that includes receiver specific calibration parameters for a RTK solution calculation. Usually a proprietary signal leads to best positioning accuracy and time to RTK fix solution in all conditions. However, proprietary messages are not compatible between different brands of receivers and therefore not commonly used, excluding Trimble's CMR that is published for public use. Other common solution is to use a protocol specified by a RTCM organization.

3.4.3 Coordinate systems and geoid model

The GNSS systems are positioning in geodetic coordinate systems, such as WGS84 and ED50. Geodetic coordinates are based on an ellipsoid that can be considered as a simplified presentation of the surface of a Earth (Picture 9). The ellipsoid is defined by a semi-major axis (a) and the Reciprocal of flattening (1/f). (Geodetic System)

Cartesian 2D and 3D system (North-East-Up, Picture 6) are easy for human beings to understand. You can draw a straight line to a map and measure its length by using conventional metric or imperial measurement tools. One can calculate a XY position for a selected distance along a circle by using trigonometry. Computer graphics are also based on Cartesian systems. For these reasons, also the design process for production models is using Cartesian coordinate systems. During the design process the XY view in the graphics can have different projections, such as road distance to elevation, but in the resulting product model X and Y coordinates define a position in the horizontal plane and Z defines a height in vertical plane. (Geodetic System)

Geodetic coordinates of ECEF system; latitude (φ) and longitude (λ) are presented in the picture 9. For example a WGS84 ellipsoid has prime meridian (X) in Greenwich that determinates the origo for the longitude. The origo for latitude follows the equator (Y). The North Pole defines the Z-axis. The Cartesian ECEF coordinates in the picture are presented as North, East and Up. (Geodetic System)



PICTURE 6. Geodetic and Cartesian coordinates (Geodetic System)

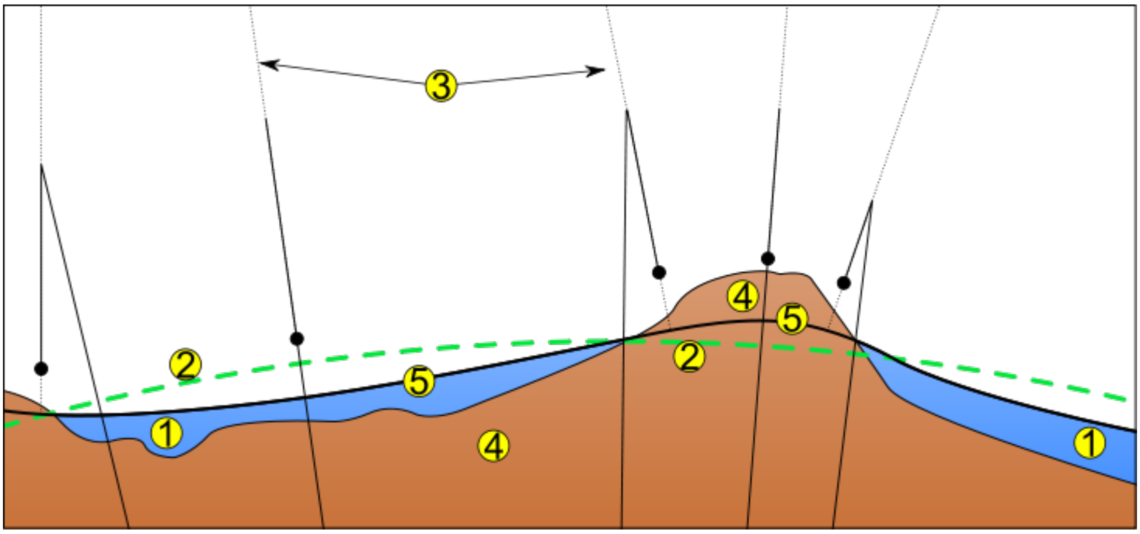
When the machine control system utilizing GNSS positioning needs to be visualized in the computer graphics or compared to a production model, a coordinate transformation is required. The geocentric coordinates are converted in to a selected reference datum. There are hundreds of reference datums, mostly because of historical reasons. In the times before the satellite navigation the geodesy was based on a line of sight observations (see chapter 3.4.4). Therefore coordinate transformations from native ECEF coordinates to local reference datums are required.

One of the transformation methods is a Helmert transformation that enables transformation from reference system A to reference system B by using three translations, three rotations and one scale parameter. Helmert is also called a 7-parameter transformation. (Helmert)

The Cartesian North-East plane can be defined by coordinate transformations but up direction (Z) is more complicated. Wikipedia explains the geoid as follows:

> The gravitational field of the earth is neither perfect nor uniform. A flattened ellipsoid is typically used as the idealized earth, but even if the earth were perfectly spherical, the strength of gravity would not be the same everywhere, because density (and therefore mass) varies throughout the planet. This is due to magma distributions, mountain ranges, deep sea trenches, and so on.
> If that perfect sphere were then covered in water, the water would not be the same height everywhere. Instead, the water level would be higher or

lower depending on the particular strength of gravity in that location. (Geoid)



1. Ocean
2. Reference ellipsoid
3. Local plumb line
4. Continent
5. Geoid

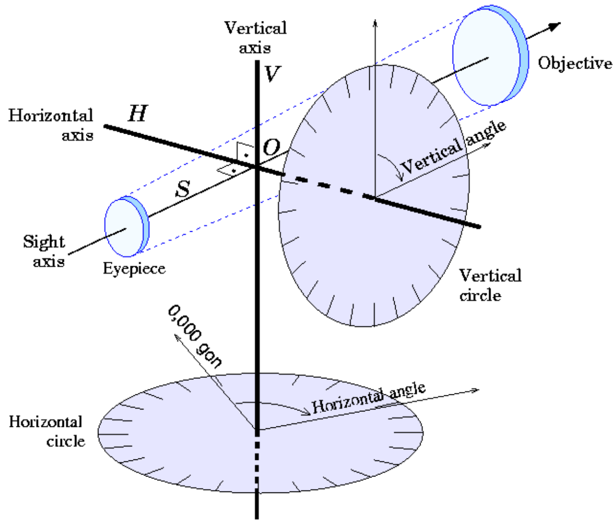
PICTURE 7. Geoid (Geoid)

This behaviour could be calibrated by the local coordinate system by simply defining a best matching plane for the current location. However, in many jobsites the normal direction of such plane is not accurate enough for precise positioning systems in centimetre level. For this reason the geoid model is used. In practice, the geoid model is a grid of elevations in known horizontal positions in relation to the reference ellipsoid.

The coordinate transformation is required for graphical presentation and for utilization of the 3D position with the production model. However, the coordinate transformations for machine control system are not always necessary. Geodetic coordinates are usable without transformation for example in simple fleet management.

3.4.4 Total station

The robotic total station is evolved from theodolite technology. Theodolites have been used in land surveying since the nineteenth century. A theodolite is an optical instrument that measures relative horizontal and vertical angles between sight points (Picture 8). If two Cartesian coordinates are known, the angle readings taken from two different standpoints can be used to calculate the coordinate for the third point. The modern version of the theodolite has digital encoders for angle measurement. (Theodolite)



PICTURE 8. Theodolite axis (Theodolite)

In addition to digital angular readings, the total station includes Electronic Distance Meter (EDM) that calculates the distance from the instrument to a reflector or object by using a modulated microwave or infrared carrier signal. The distance reading eliminates the need for two standpoints and enables the real-time calculation of the reflector position. Before the position of the reflector can be determined the position and orientation of the robotic total station needs to be determined. Usually two or more known coordinates are sighted and the computer inside the unit calculates the position and orientation of the equipment.

The robotic part of the total station is implemented by adding servomotors that drive the horizontal and vertical angles of the equipment. The total station is usually operated by a remote control to reduce the amount of the required personnel for measurement. In the machine control application the real-time position is transmitted to the machine via one of the commercially available radio bands, such as UHF or 2.4GHz. The teleoperation and position communication link can also be integrated, and the position can be output from the remote controller.

The robotic total station is used in applications where the accuracy requirement is below the accuracy of GNSS RTK technology or when the GNSS does not have the coverage. The accuracy of the robotic total station is typically around 2mm + 2ppm. The only downsides for robotic total station applications are:

- The line of sight between reflector and robotic total station required
- Position and orientation determination is time consuming

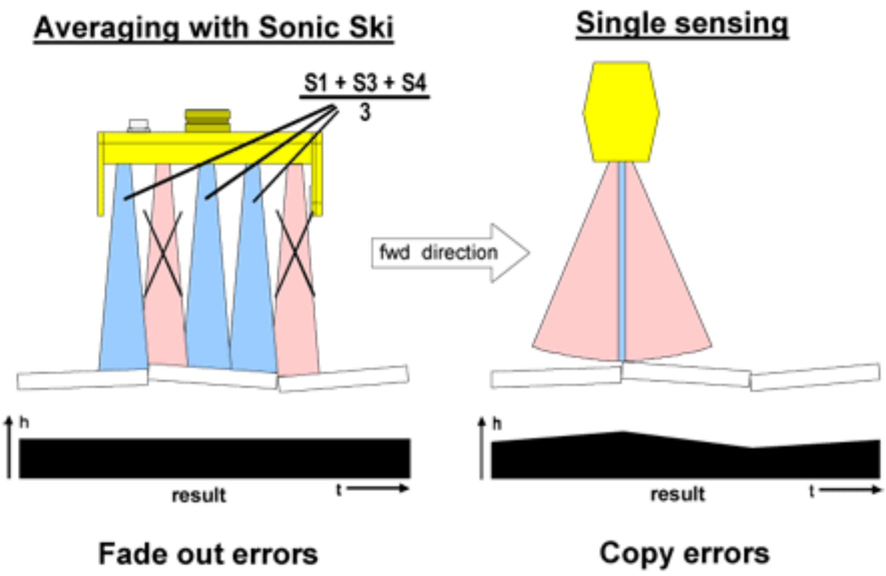
In 2012 the price of the robotic total station is roughly twenty-five thousand Euros. (Total station)

3.5. Other positioning sensors

GNSS and robotic total station technologies are the most common 3D positioning sensors. In some applications the price of the two technologies is too expensive for the customer.

The combination of laser level and the laser receiver is a more affordable way to position the height of the machine. Usually the laser beam rotates continuously around the laser sensor in the speed of 300 to 1000 revolutions per minute. The digital laser receiver is used to catch the laser beam. The precision of the laser transmission is typically down to millimetres, but it depends on the amount of photo-diode channels in the receiver and their mechanical displacement to determine the height accuracy of the laser levelling application.

Other interesting height sensing technology is the ultrasonic transceiver. In the transceiver, a modulated ultrasonic sound wave is transmitted from the sensor element and when sound is reflected from the object, the sensor receives the echo and time of flight is calculated. Moba AG has developed a unique Sonic-Ski® sensor that calculates the distance from ground or string line by using multiple ultrasonic transceivers.



PICTURE 9. Ground sensing with Moba AG Sonic-Ski® (Moba)

3.6. Machine control software and processing

Functionality requirements vary quite a lot in different levels of autonomy and in different applications. In this paper the perspective is in the 3D guidance and control. The main purpose of the 3D application software is to present GUI for the operator of a machine. Other main functionalities include:

- Interface to inner-state and positioning sensors
- Interface to production models
- Machine absolute position and orientation determination
- Calculation of deviations between the position of the tool and the production model
- Interface to control system
- Communication

The modern machine control GUI is based on a game engine or a similar technology that is capable of rendering 3D objects, such as lines, points and triangle meshes and presenting them in the display. 3D capability is not only a software issue. There are multiple graphical API options with different level of hardware integration. The production model for an information rich civil engineering jobsite sets the requirement to use GPU, hardware acceleration for graphics.

3.7. Production model and as-built data exchange

The Designer or Surveyor designs the production model. The production model describes the work by means of a virtual model created by CAD system. Production model can have different level of detail and information depending on:

- The type of jobsite
- The quality of original design
- The amount of added data by jobsite personnel

In practice the work is modelled by using drawing tools of the CAD system. Typically design and survey systems in civil engineering have similar tools to their relatives in mechanical engineering. For an example the centre line of the road can be modelled by drawing a poly-line object calculated from lines, curves and spirals.

Most of the street and road design follows a set of rules and therefore an efficient CAD work requires rule based modelling tools. In spite of how the design has been done, usually the end result for the construction phase is very simple containing pre-calculated lines and surfaces.

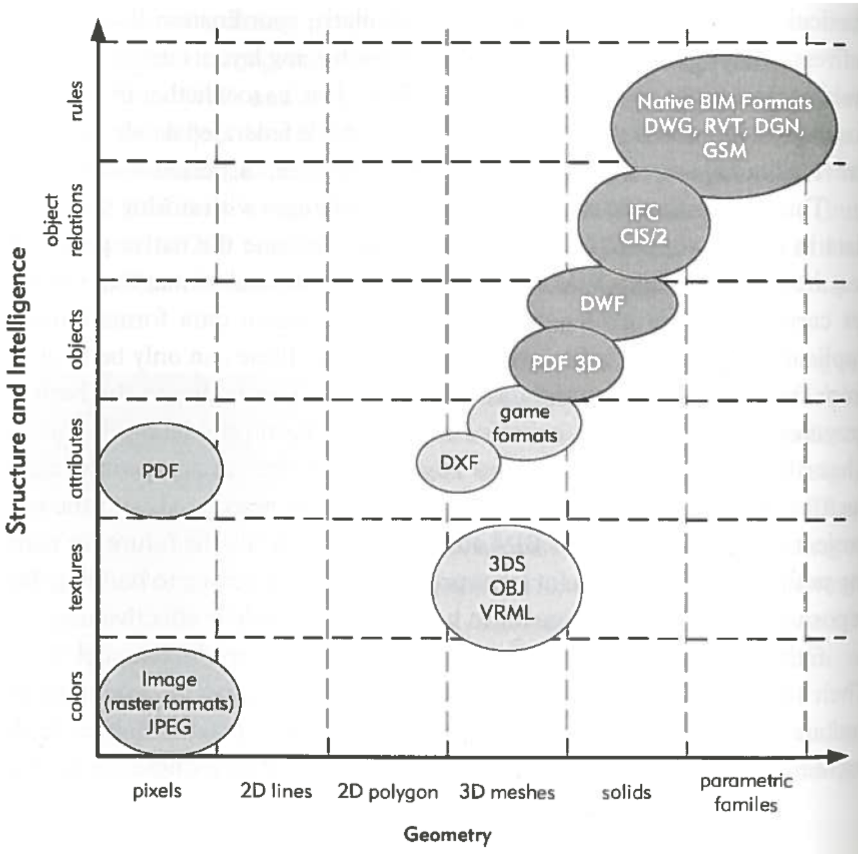
Most of the construction phase models for the machine control have been inherited from the GIS world, where non-object based: geometry lines, drawings and DTM have been used since the end of the 1980's.

In this work the type of data is separated in to following parts:

- Drawings (Chapter 3.7.3)
- Digital Terrain Models (Chapter 3.7.4)
- Road models (Chapter 3.7.5)
- As-built data (Chapter 3.7.6)

3.7.1 Intelligence of data exchange format

Eastman et al. compares the popular data exchange formats according to the geometry support and intelligence (Picture 10). The common formats used by measurement systems including the machine control implements the level of DXF and game formats. This level is sufficient for most of the construction tasks but there are a lot of tasks, especially in the field of accessories and underground structures that would benefit from more intelligent formats. (Eastman et al., 2008, 67-91)



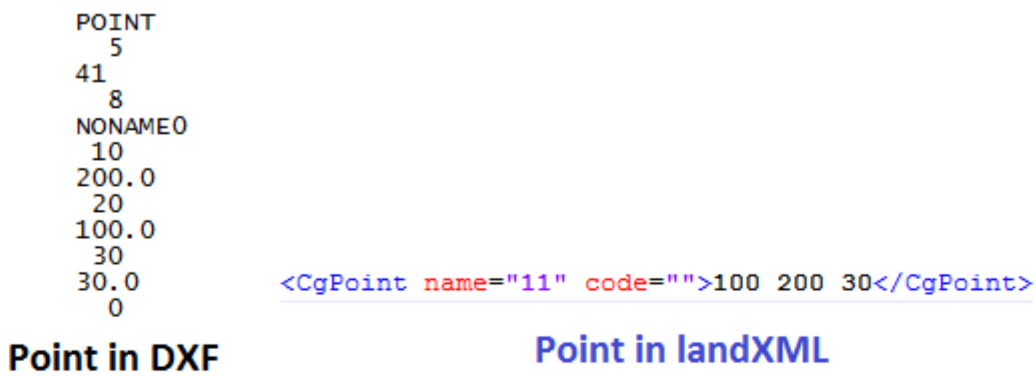
PICTURE 10. Intelligence of data format (Eastman et al., 2008, 90)

There are also pro's and con's for the intelligence of the data. Usually intelligent models require smaller space for data storage and bandwidth because the model is not completely pre-calculated. The biggest opportunity for the operator of the machine with more intelligent and powerful model is to finish the task more efficiently and with increased quality. One example is a light pole installation where a common solution today is to model one part of the object by a single 3D position. By using this model the operator could install the light pole easily to a wrong height because he/she does not know if the position tells the height for the excavation, bottom of the feet or top of the feet. A more intelligent model would define the heights for all parts of the object and also determine the orientation of the light pole. An intelligent model is also required for efficient life cycle management of the product model.

When the level of intelligence is increased to solids and parametric families, the creation logic of an object needs to be well known and precisely implemented in all applications utilizing the format. Increased complexity lifts the bar for taking the responsibility of 100% correct interpretation of the model. When creating a roadbed with a set of rules, a very small error in the code can lead the road to be calculated to a wrong place. The calculation error might not be found before an implementation of other supplier is used to calculate the same object. This kind of small programming error could cost millions of Euros in a single road construction project. Therefore a less intelligent model could be used because of safety reasons.

3.7.2 LandXML

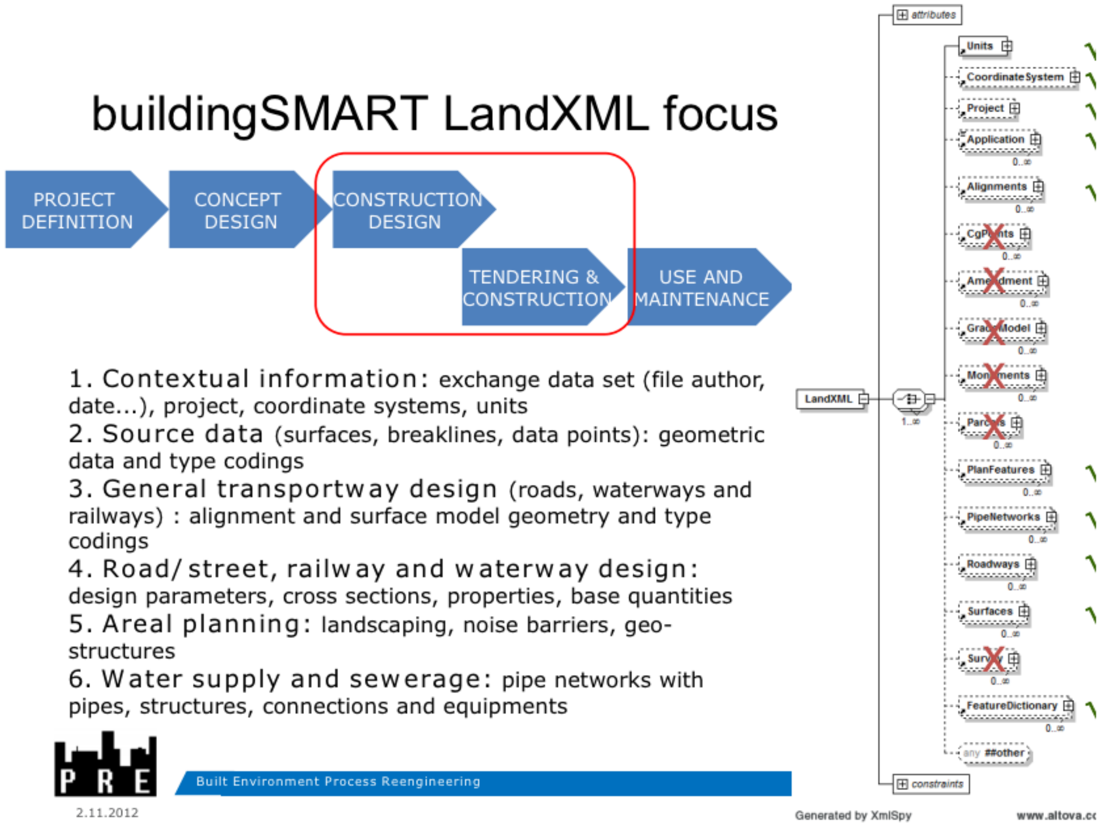
LandXML is an open, non-proprietary data exchange format that loosely determinates a XML schema for civil engineering purposes. The schema has elements for different GIS and BIM purposes including geometry lines (alignments), digital terrain models (surfaces), pipe networks, parcels, coordinate system and other contextual information. The XML format supports object based data structure and therefore LandXML can be considered a more intelligent format than DXF (Picture 11). The difference simplified is that LandXML explains better what is the purpose of an object.



PICTURE 11. Example of point object in DXF and LandXML formats

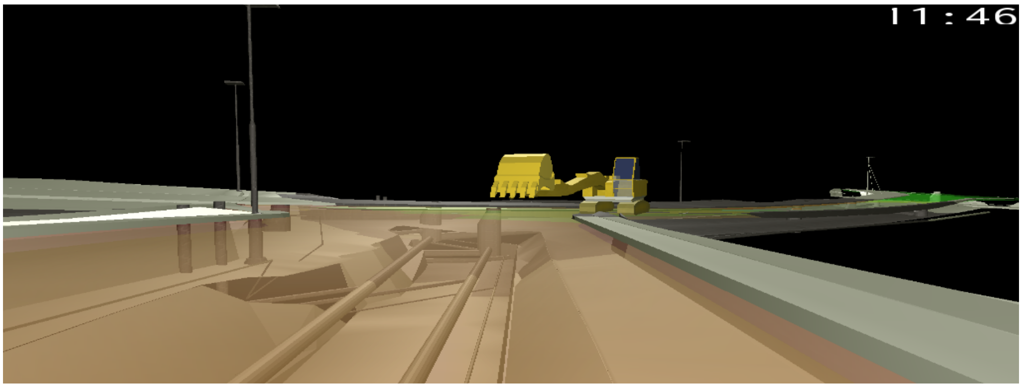
The original LandXML format and its successors are implemented to several design and measurement systems, but without a consistency or a perfect interoperability between two systems. Even though LandXML is a more intelligent format it leaves too many options to describe complete structures like roads for a construction phase. At the time being, there are at least five different ways to export a complete road object.

For this reason a more precise standard has been specified on top of the LandXML standard in a Finnish research project. This standard is called Inframodel 2. Today it seems that the LandXML format is finding its new homes from two different places, the BIM side from buildingSMART organization and the GIS side from OGC. The buildingSMART ITM/IUG has accepted the new project proposal by its Nordic chapter, titled “OpenINFRA: BuildingSMART MVD for LandXML v1.2”. The project has the base in inframodel 2 definitions. The focus of the work can be seen in picture 12. The content supports the Automation in Civil Construction jobsite. (Inframodel; Hyvärinen, 2012).



PICTURE 12. LandXML in buildingSMART

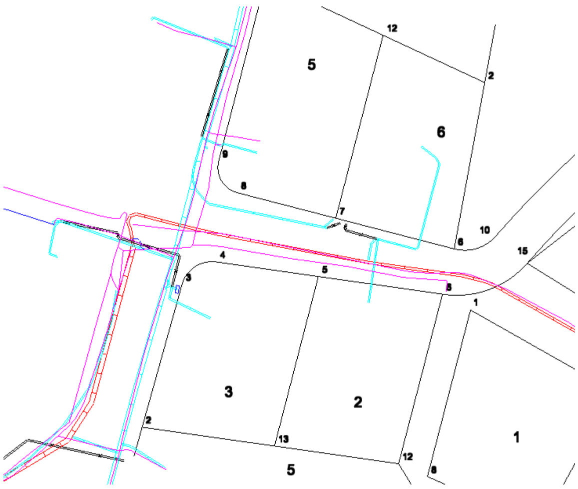
The resulting format might allow an approximately similar result to the visualization of machine control system running imaginary Inframodel 3 in picture 13. Here the operator of the machine can see all the construction layers at once together with underground structures and other installations such as light poles. There will follow the problem of how to visualize the increased amount of information for the operator in the GUI.



PICTURE 13. Inframodel 3 format

3.7.3 Drawing

The simplest type of a production model is a drawing that presents the jobsite in a printable map form. It consists lines, curves, text objects and points. A notable matter is that in many cases even if 3D product modelling is used, the orthogonal 2D drawings are clearest for human eye for assembly and measurement purposes and therefore also a lot used in the field applications.



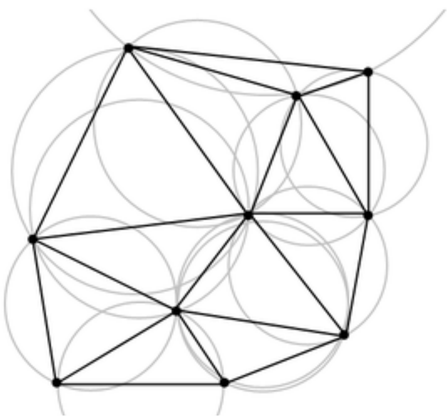
PICTURE 14. Drawing in Topocad 14.

Drawings can be used in a Machine Control system for positioning the relation of the machine to the objects in the 2D drawing horizontally. This is fully sufficient for example if the operator should care for underground structures like electric cables. 2D drawing could be used to finish tasks in 3D if the height for the object is written as a TEXT object in to the drawing. The drawing could also been implemented in 3D or it could be a presentation of a 3D model. In this case also the relative 3D measurements are enabled for the machine control system.

3.7.4 Digital terrain models

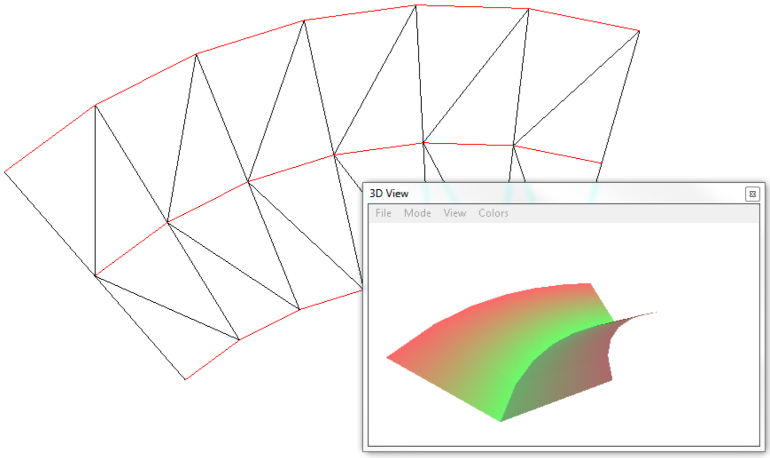
The digital terrain model contains points and definitions how they are connected together to form a surface. The most used terrain model in civil engineering is a TIN. The TIN is formed using an algorithm that creates the best possible interpretation of a surface by connecting the triangles of the 3D source data points (Picture 15). The most famous algorithm for a TIN surface creation is called the Delaunay triangulation that is actually a quite close relative to trilateration. Wikipedia explains the Delaunay algorithm as follows:

> ”Delaunay triangulation for a set **P** of points in a plane is a triangulation DT(**P**) such that no point in **P** is inside the circumcircle of any triangle in DT(**P**). Delaunay triangulations maximize the minimum angle of all the angles of the triangles in the triangulation; they tend to avoid skinny triangles.” (Delaunay)



PICTURE 15. Delaunay triangulation with triangles and circumcircles (Delaunay)

It is possible to draw and select 3D objects in the CAD system for the triangulation algorithm. The algorithm calculates the 3D points of geometry data such as arc and spiral according to desired accuracy level. The triangulation algorithm is then performed for the point source data and the TIN is formed. (Picture 16)



PICTURE 16. Triangulation of three arcs in Topocad 14.

The TIN surface can be exported to LandXML format. All point coordinates and connecting faces are described. (Picture 17)


```
- <Surfaces>
  - <Surface name="three-arcs">
    + <SourceData>
    - <Definition elevMax="0.300" elevMin="0.000" surfType="TIN">
      - <Pnts>
          <P id="1">100.336181894596 201.283451534493 0.3</P>
          <P id="2">100.480824524051 201.480262020978 0.3</P>
          <P id="3">100.590911766532 201.698291048606 0.3</P>
          ...
          <P id="19">101.639685634174 201.715000838376 0.3</P>
          <P id="20">101.68222308441 202.531595559721 0.3</P>
          <P id="21">101.694964796626 202.121526552419 0.3</P>
        </Pnts>
      - <Faces>
          <F>9 10 3</F>
          <F>10 5 3</F>
          <F>9 3 2</F>
          ...
          <F>12 14 18</F>
          <F>18 14 20</F>
          <F>20 15 21</F>
        </Faces>
      </Definition>
    </Surface>
  </Surfaces>
```

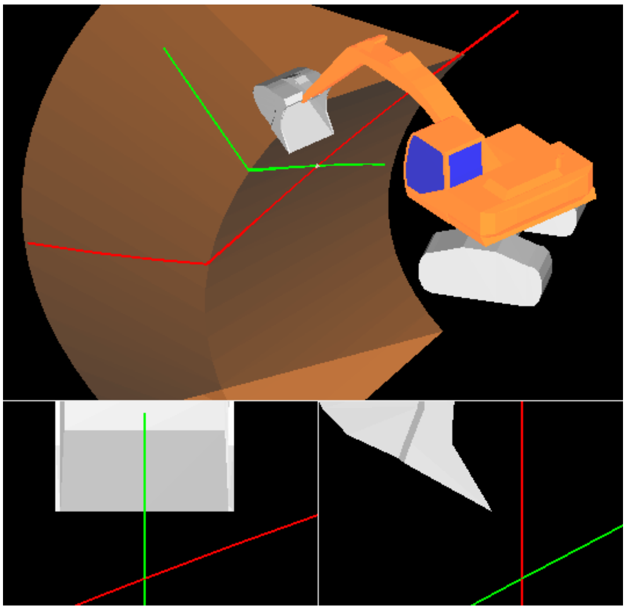

3D points

Face description. Each face having three points.

PICTURE 17 LandXML TIN surface

The most popular application of TIN models in civil engineering is a volume calculation between two models. This is very important information because most of the cost in a civil construction project is based on mass hauling.

The very same surface models and techniques can be used in the machine control system. The surface model describes the fill or cut work. The processing system finds the triangle where position of the tool is located in real-time. The located triangle is ray-casted in the direction of Z-axis as long as the crossing hit point in the triangle is found. If orientation of the tool is known, the triangles normal vector can be used to calculate the slopes of the surface according to working direction of the tool (Picture 18).

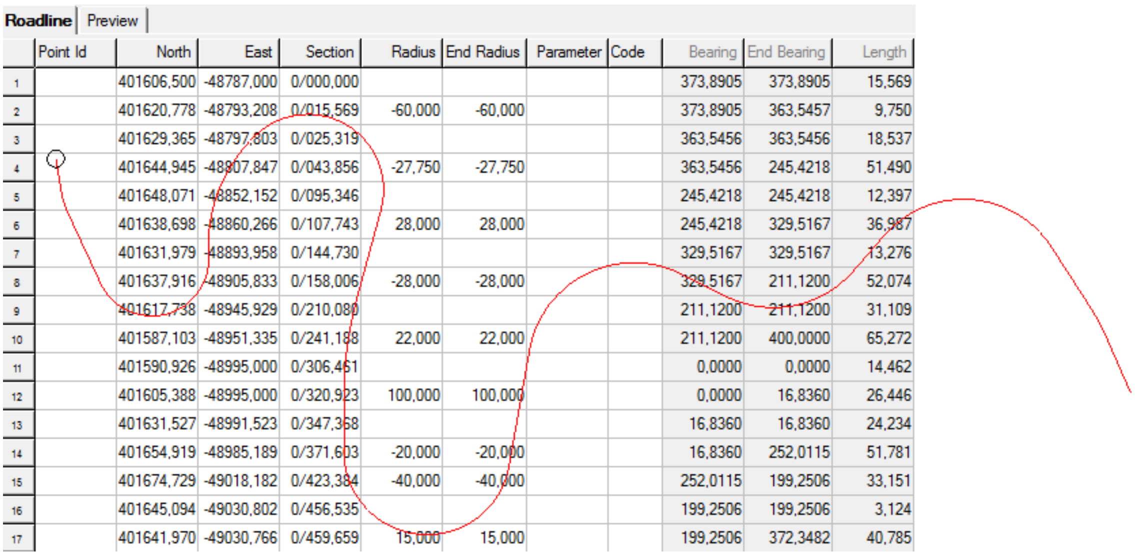


PICTURE 18. TIN model in machine control system

DTM can be used in numerous different tasks. There are some jobs that need more intelligence than just a set of connected point cloud. One example of such application is an automatic 3D motor grader blade control where more precision is required for slope and height deviations.

3.7.5 Road models

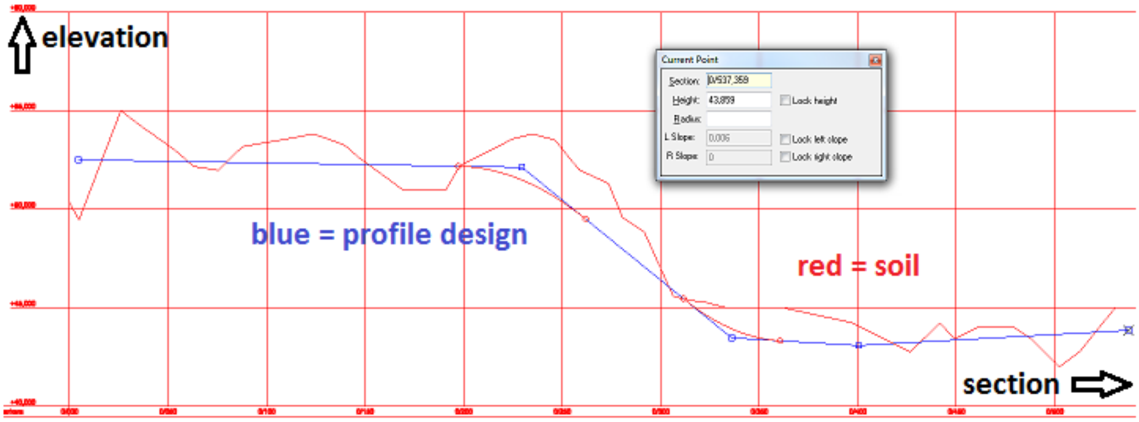
When a road design project is started, the first decisions affecting to the work plan and to the required mass haul of the production model are done in the early feasibility-planning phase. In this phase a single alignment is modelled to an existing surrounding. The alignment is made in two parts, by modelling the horizontal and vertical alignment. The horizontal part consists of lines, curves and spirals. The alignment start point has a station number that is increasing step by step along the alignment in used distance units. The parametric format of the horizontal alignment together with its preview is visible in picture 19.



	Point Id	North	East	Section	Radius	End Radius	Parameter	Code	Bearing	End Bearing	Length
1		401606,500	-48787,000	0/000,000					373,8905	373,8905	15,569
2		401620,778	-48793,208	0/015,569	-60,000	-60,000			373,8905	363,5457	9,750
3		401629,365	-48797,803	0/025,319					363,5456	363,5456	18,537
4		401644,945	-48807,847	0/043,856	-27,750	-27,750			363,5456	245,4218	51,490
5		401648,071	-48852,152	0/095,346					245,4218	245,4218	12,397
6		401638,698	-48860,266	0/107,743	28,000	28,000			245,4218	329,5167	36,987
7		401631,979	-48893,958	0/144,730					329,5167	329,5167	13,276
8		401637,916	-48905,833	0/158,006	-28,000	-28,000			329,5167	211,1200	52,074
9		401617,738	-48945,929	0/210,080					211,1200	211,1200	31,109
10		401587,103	-48951,335	0/241,188	22,000	22,000			211,1200	400,0000	65,272
11		401590,926	-48995,000	0/306,461					0,0000	0,0000	14,462
12		401605,388	-48995,000	0/320,923	100,000	100,000			0,0000	16,8360	26,446
13		401631,527	-48991,523	0/347,368					16,8360	16,8360	24,234
14		401654,919	-48985,189	0/371,603	-20,000	-20,000			16,8360	252,0115	51,781
15		401674,729	-49018,182	0/423,384	-40,000	-40,000			252,0115	199,2506	33,151
16		401645,094	-49030,802	0/456,535					199,2506	199,2506	3,124
17		401641,970	-49030,766	0/459,659	15,000	15,000			199,2506	372,3482	40,785

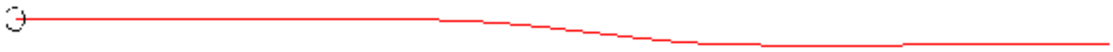
PICTURE 19. Horizontal alignment in Topocad 14. Picture modified.

The vertical part consists of station numbers along the alignment and corresponding elevation readings (Picture 20). The red line is calculated from DTM and the horizontal alignment presenting the surface soil of the existing environment. The designed profile form in picture 20 is presented in parametric format in picture 21. Note the scale difference in elevations between the profile form and the parametric preview. (VHB, 2007, Chapter 4)



PICTURE 20. Soil and vertical profile design in profile form in Topocad 14

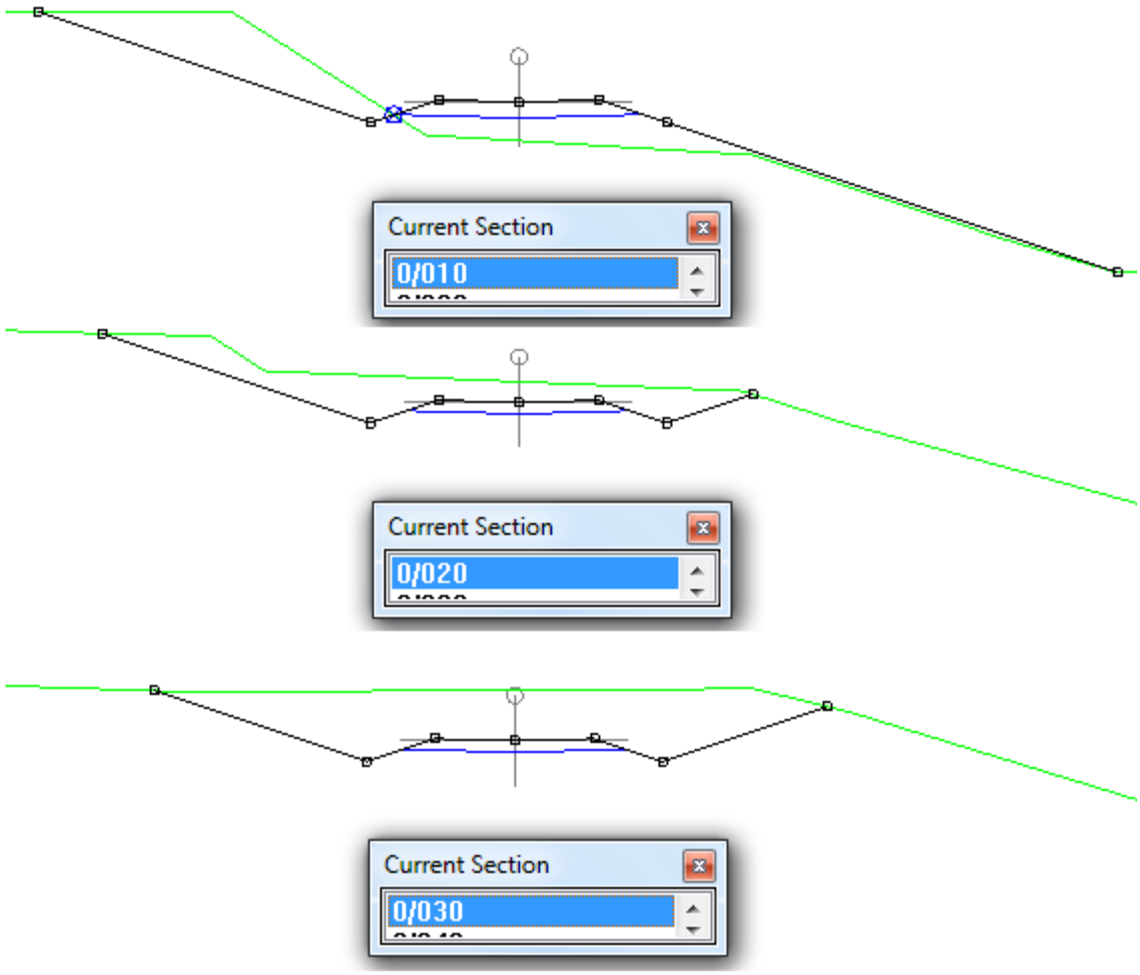
Profile	Preview						
Point Id	Section	Height	Radius	Start Slope	End Slope	Length	Clothoid param
1	0/004,522	52,510		-0,17%	-0,17%	192,681	
2	0/197,203	52,183	-815,446	-0,17%	-8,129%	64,687	
3	0/261,890	49,502		-8,129%	-8,129%	49,653	
4	0/311,543	45,466	652,976	-8,129%	-0,595%	49,022	
5	0/360,565	43,330		-0,595%	-0,595%	39,757	
6	0/400,322	43,094		0,559%	0,559%	137,037	
7	0/537,359	43,859		0,559%			



PICTURE 21 Vertical alignment in Topocad 14

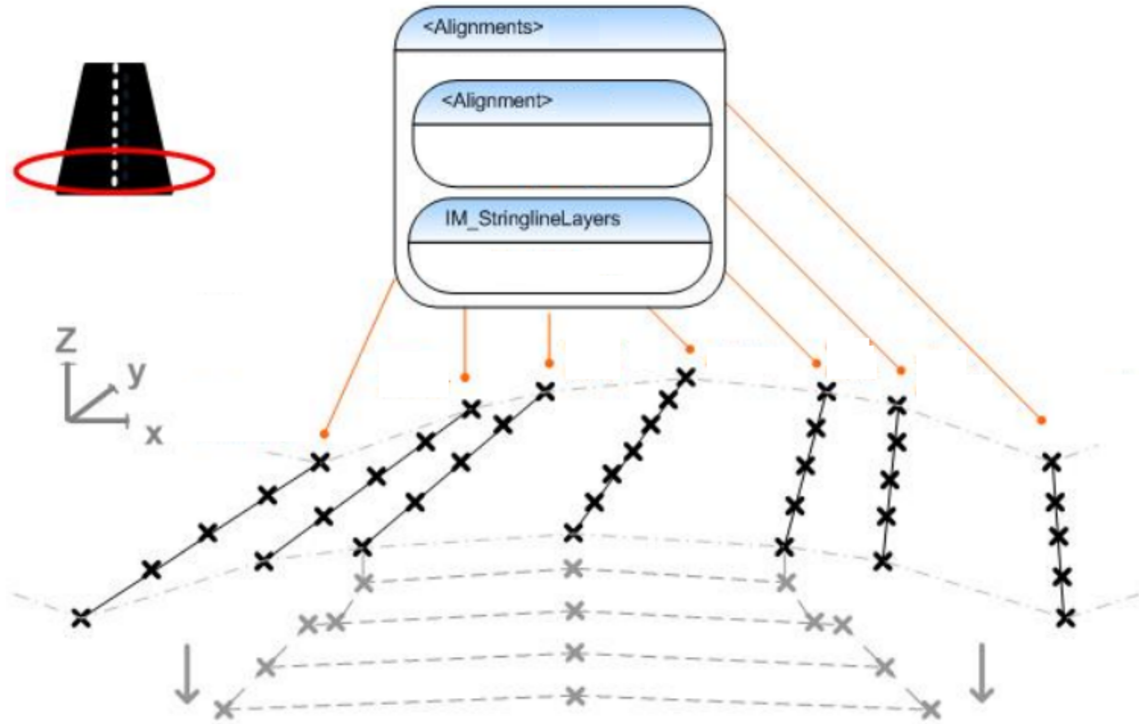
Both horizontal and vertical alignments have design rules that set the limits to maximum curvature in both profiles according to road type and speed limit. The idea is to design a safe road for motor vehicle traffic. (VHB, 2007, Chapter 4)

Next part for the complete road design is a cross-section. The cross-section determinates the lane width of the road, together with drainage and quality properties. Usually the road has a basis on a pre-defined typical road cross-section. The behaviour of calculated cross-sections is based on a set of rules. Picture 22 shows the calculated cross-sections for the alignment and soil information above. Here you can see that the CAD system automatically calculates the position where the last slope (black line) intersects with the soil (green line) according to rules.



PICTURE 22. Cross-section in stations 10, 20 and 30 in Topocad 14

The road models are very complicated to interoperate to the other CAD system and machine control. This is because there is no standardized format to export parametric structures. Even then the problem would be exporting all the rules of how the 3D surface should be formed in the 3rd party application. This level of intelligence in data format would lead to better quality in the construction phase if the surface were interpreted correctly in the measurement system. This can be done at the time written only by using proprietary formats or by using separately agreed rules. However, intelligent data exchange is more important for design-to-design data exchange. The machine control systems and other measuring instruments require a good compromise for a road model with mostly pre-calculated data. The requirement is to interpret all constructed layers at once, enable sideline measurements and station number calculation. This could be achieved by using a LandXML format with additional agreement how it should be used. One example of such data format could be found from the inframodel 2 specification (Picture 23).



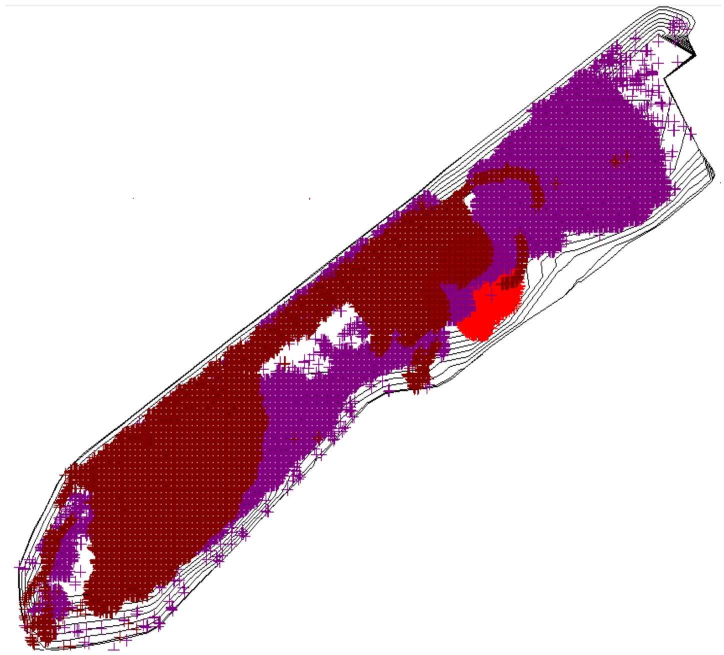
PICTURE 23. Inframodel 2 format and Stringlines. Picture modified (Inframodel)

All sidelines in the format described in picture 23 are calculated to the poly-lines so application interpreting the information does not require to known the surface calculation rules. The format allows the accurate slope measurements in a selected road direction because alignment information is exported. This is one advantage against a simple DTM format where the direction of the road is not known. In writer's opinion this is the level of intelligence suitable for machine control systems.

3.7.6 As-built data and quality assurance

As-built data is typically a 3D point or line object containing code and point number information. The coding is usually used to identify the type of the object. The point number identifies the measured instance. The problem in the current method is that the unique identifiers for different objects do not exist. If one would like to import the As-Built data of today in to the information model, a rough assumptions about the content of the information needs to be done by its location.

Simple as-built data is fully sufficient for simple cases. One example is a dredging system where the machine automatically logs the positions where the bucket has reached the production model in set tolerance. In the picture below the logged data from the different dredging sessions are loaded to a CAD system for further analysis (picture 24).



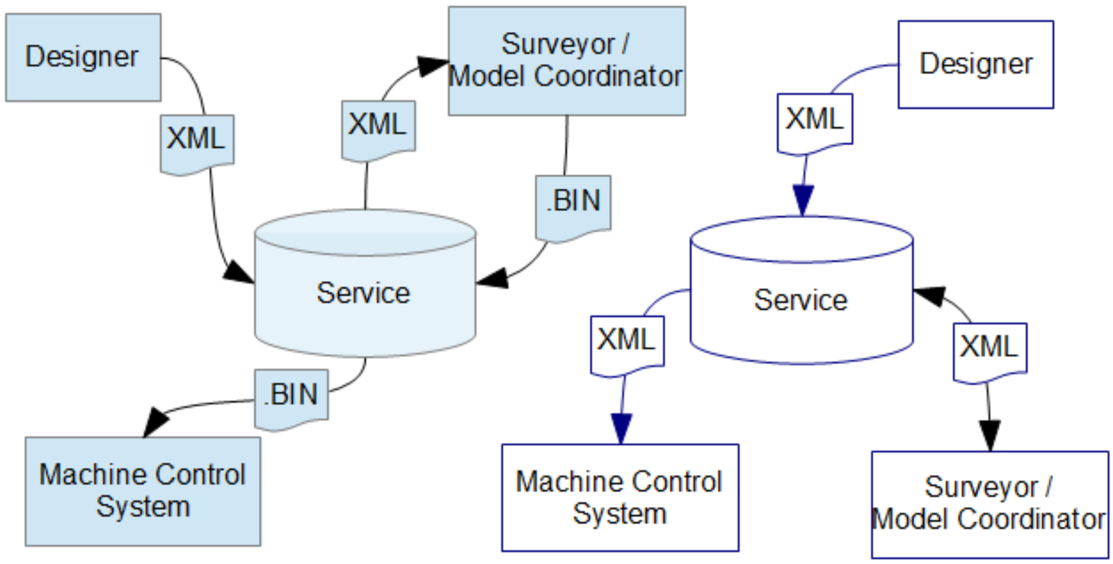
PICTURE 24. As-built data from dredging barge in Topocad 14.

The operator of the machine can store the as-built data also manually. The stored data is usually a coded point information. The points can be exported to a file format, such as LandXML.

Quality assurance means measuring the accuracy of the machine control systems and accuracy of the built layers systematically. Novatron has a built in tool for tracking the accuracy of the machine control system. When a set time limit is achieved the system requires an accuracy check against a known fixed point from the operator of the machine.

3.7.7 Production model data flow

There are two common data flows to supply a production model from a designer or surveyor to the work machine and its machine control system. The first option is to export the model in a standard file format to the separate application that converts the data to a proprietary format. Another option is to skip the conversion part and read standard formats in the machine control system. The separate conversion tool has pro's and con's. With a conversion tool the model can be verified before testing the compatibility on the field. In the other hand, if compatibility can be trusted it is a time consuming task to handle for each model. Other advantage of reading standard or well-known data formats directly is the process flow. If data can be transferred directly from the designer to a machine control system, the need of installing and using a conversion tool is out of the picture. However, the product model can be viewed and managed by jobsite personnel if required.



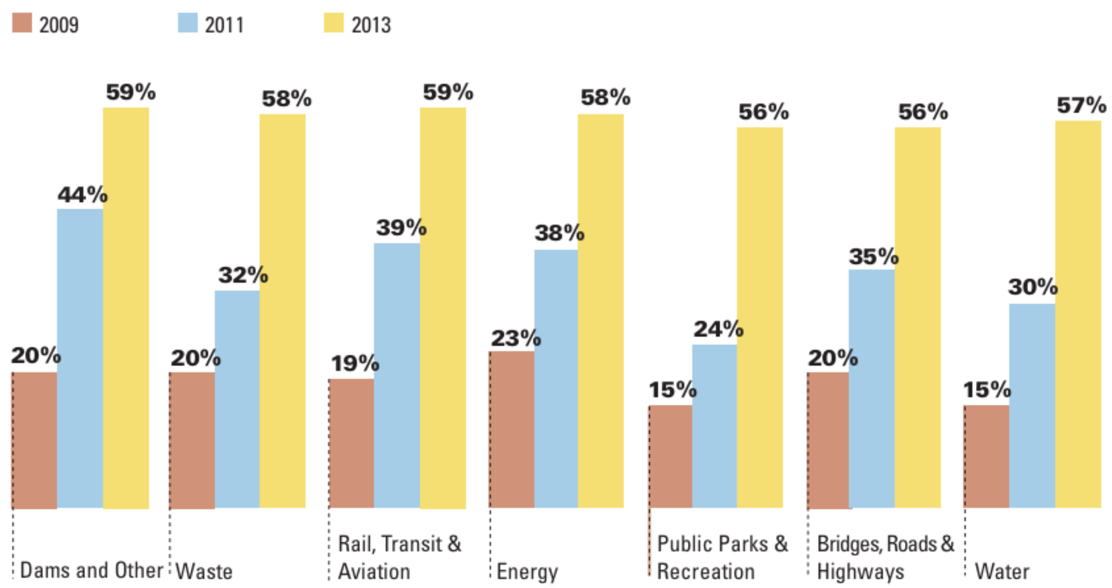
PICTURE 25. Data flow with (on the left) and without (on the right) proprietary file formats.

4 CIVIL CONSTRUCTION

The Institution of Civil Engineers describes the civil engineering as follows:

> Civil engineering is a professional engineering discipline that deals with the design, construction and maintenance of the physical and naturally built environment. Put simply, civil engineers build bridges, roads, canals, dams, tall buildings, and other large structures. (ICE)

There is different kind of construction jobsites in civil engineering area that would benefit of advanced real-time process control in the construction phase. Smart Market Report survey implemented by McGraw-Hill Construction (Picture 26) shows that most important infrastructure project types for machine automation share almost the same figures by BIM implementation percentage. Therefore there is no particular need to focus on any specific project type in this study; the benefits of the BIM process could be considered equal between the project types. Most of the writing is done the road jobsite in mind because it is considered to test the most of the requirements. The first two chapters describe the normal project life cycle and its stakeholders. In the third chapter the most common management methods are presented. The last chapter sums up and generalizes the key findings.

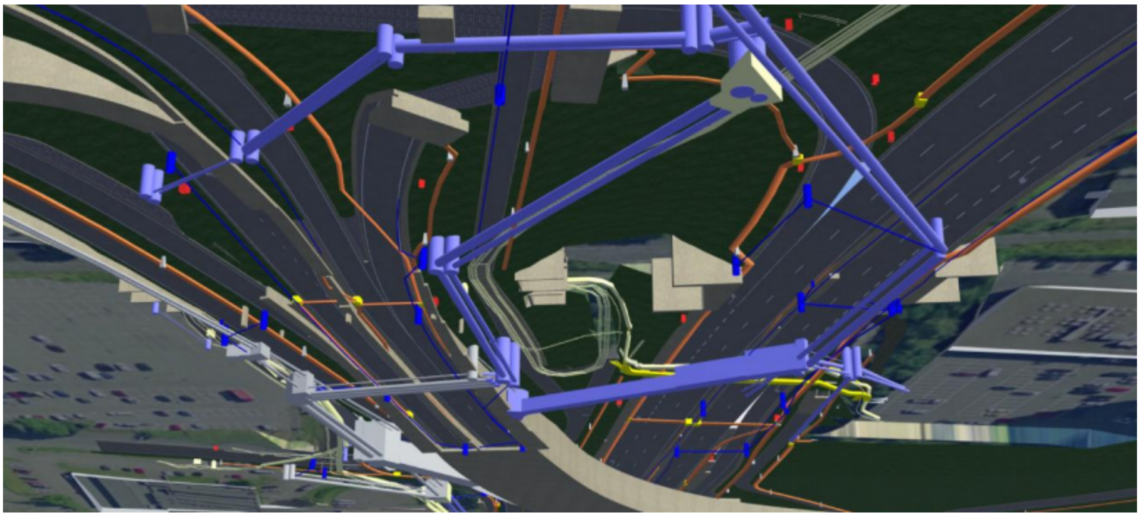


PICTURE 26. BIM implementation on More than 50% of Infrastructure Projects by Project Type (McGraw-Hill Construction, 2012)

4.1. Building Information Modelling

The BIM for civil construction has been researched actively since the beginning of the millennium. Now it seems to take the first steps towards implementation in practice. The BIM thinking helps the interoperability of the systems and is therefore one of the enabler of the civil construction production control system.

BIM is a process rather than a model. BIM, as it is understood today involves the concepts, approaches and methodologies dated back to nearly thirty years (Eastman et al., 2008, xi). The basic idea of the BIM is the collaboration during the different steps of the product life cycle. The relevant, resulting output data is passed from a step to another in digital format. The product model evolves in every step by information such as plans, multi-technical 3D design files, as-built and QC/QA data. The multi-technical design data can be integrated in to the virtual integration model for clash detection (Picture 27). With the integration model the work group's expertise can be utilized for problem solving. This leads to the better designs and saves the money by tackling the problems before they are faced on the jobsite. (Eastman et al., 2008, 207)



PICTURE 27. Novapoint VirtualMap integration model (Halttula, 2012)

The design cost in the construction is relatively small in comparison to the cost of the construction. However, the most of the cost is determined already in the preliminary planning. One basic difference when using the BIM process is that more effort is placed on early planning and design. The relation of planning effort and ability to impact on cost can be seen in the figure 3.

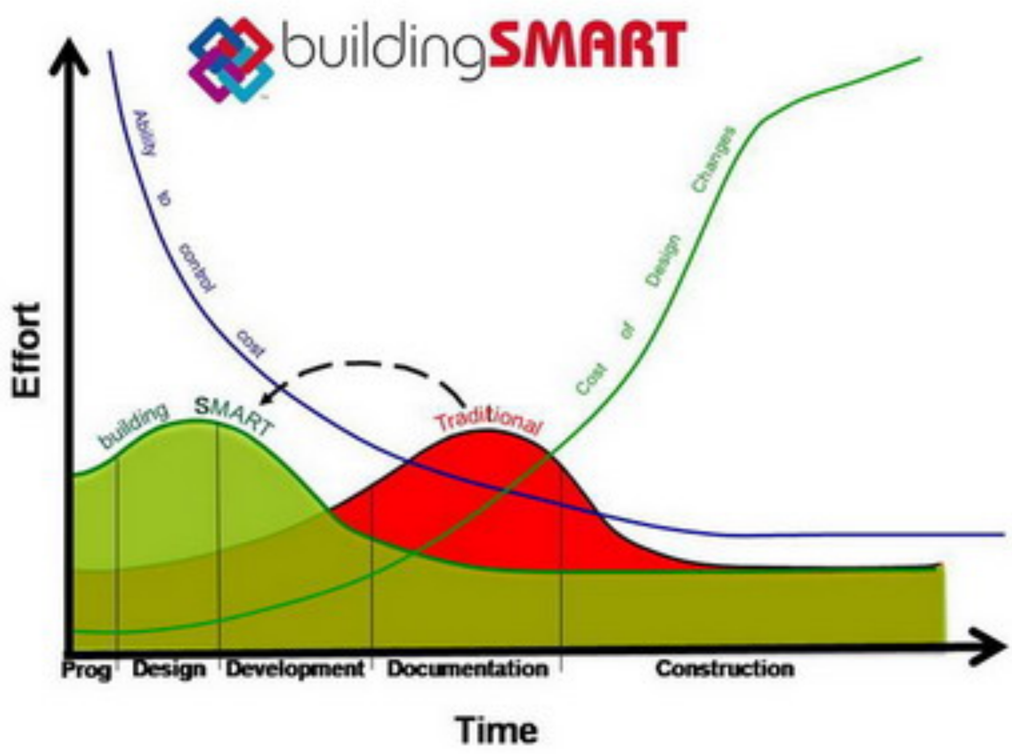


FIGURE 3. Ability to Control Cost and Cost of Design Change (MacLeamy, 2010)

In the picture 30 the life cycle of the design work is separated to programming, design, development, documentation and construction. Hendrickson describes the life cycle of the product (Figure 4). In this picture the input interface to construction is ‘Construction proposal’ and output interface is ‘Completed’. The most interesting part here is the abbreviations: Computer Aided Engineering (CAE), Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM). The machine control system together with automated production control would justify the use of term CAM in civil construction jobsite.

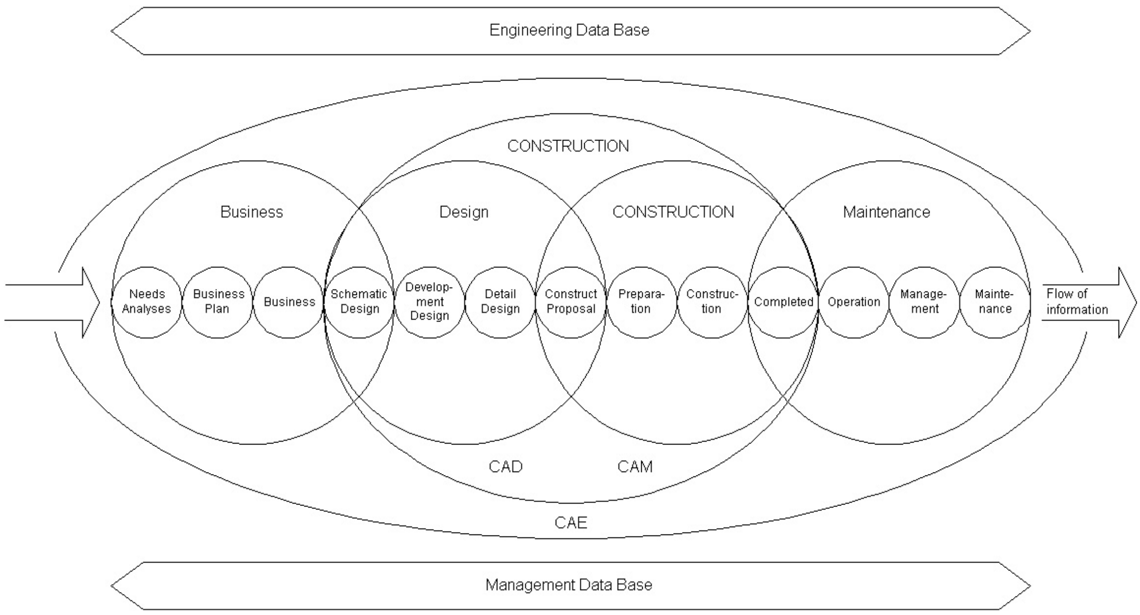


FIGURE 4. Computer aided engineering in the construction industry (Hendrickson, 2008)

Heikkilä et al. presents another product life cycle model from the point of view of construction automation (Heikkilä et al., 2009):

1. Initial Measurements
2. Product Modeling and Design
3. Construction Control and Machine Guidance
4. Quality Assurance and Control (QA/QC)
5. Lifecycle Operations and Maintenance

In this model the programming is not relevant and is excluded. Steps one and two are included to design, development and documentation phases. Steps three and four are included to the construction phase and step five is seldom maintenance. This work focuses on construction and therefore only interfaces to design and maintenance phases are discussed. Programming related issues, such as contracting methods and maintenance related, such as infrastructure diagnosis parts are excluded from the study.

4.2. Civil Construction Stakeholders

There is no single solution how jobsite personnel are divided to different roles. The amount of personnel in the project depends greatly on its size. The aim for process control product is focused on jobsites bigger than one million Euros and smaller than 100 million Euros. Bigger projects are usually divided into smaller sub-projects, so in this case the product should fulfil the basic requirements of the sub-project. The modern model-based project includes following personnel (Hendrickson, 2008; Kemppainen, 2012):

- Owner. Orders the design and construction work
- Designer. Designs a road geometry, a bridge, an underground structure or similar for construction.
- BIM coordinator. Integrates the multi-technical design files from the different sources to a single integration model. Verifies the plans by using clash detection and other tools. Exports data for measurement instruments and machine control. Collects as-built and QA/QC data.
- Project management. Ensures that the project stays in schedule and in budget.
- Supervisor. Sets and follows the activities.
- Sub-contractor, machine owner. Sells resources to the jobsite. Is responsible for the condition of the work machines.
- Operator of the machine. Implements the jobsite tasks and is responsible for checking the machine control accuracy of the system.
- Surveyor. QA/QC, assists in the use of machine control systems

In practice the work can be divided to different consultants and to several sub-contractors. There might arise needs for reporting to owner or owner’s consultants as well. Therefore very flexible organization structures and role definitions need to be allowed in the production control system.

4.3. Before construction phase

The quality of the design is very dependent on the owners purchasing methods and the quality of initial measurements. For initial measurements, the laser scanning and photometry techniques are used to determine the shape of the soil and its attributes. The underground soil features determination is technically far more complicated and is usually done by taking samples (Heikkilä et al., 2009). Underground soil features, such as the level of rock are an important attribute for designing the mass balance of the project. The mass balance plan is a crucial part of the whole life cycle of the projects. The early decisions have the greatest impact on the total cost as seen in picture 30. The alignment and mass balance planning are an iterative process to find the best possible compromise that fulfils the owner's requirements. (Manninen, 2009, 67)

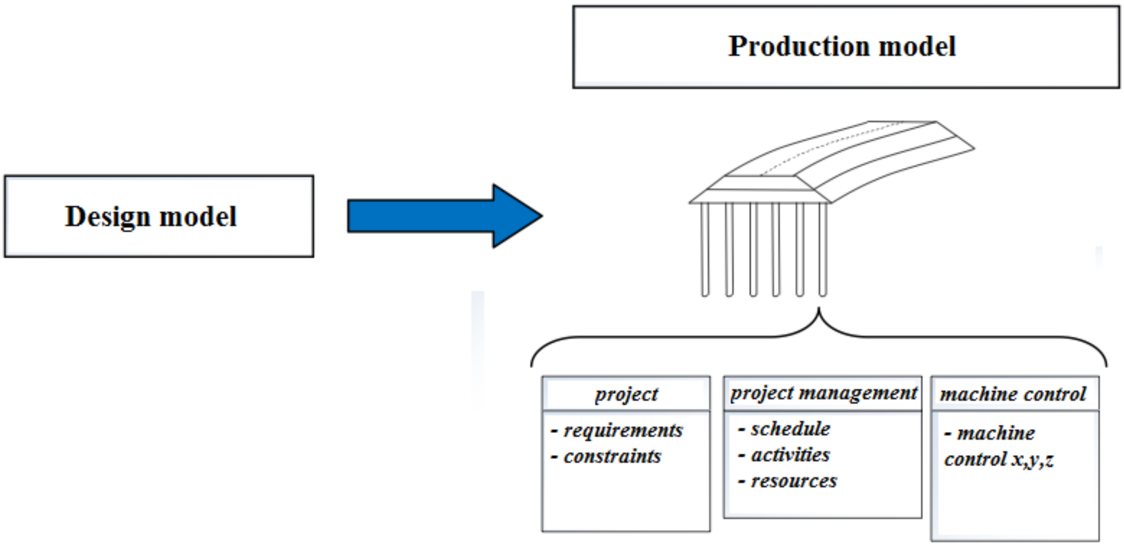
The preliminary plan and the design of the project could have been done with very low resources and many years before it is triggered further to the development or construction (Mikkonen, 2012). If the original plan is old, it is very likely that its quality is not in the level of modern 3D design. These drafting-centric 2D design files needs to be updated to the 3D before they can be utilized fully in the automated construction. The decision needs to be made if the 2D design is modeled to 3D or if the possible risks are shifted to the construction phase.

When design was made in 2D the most of the design problems, like clashes between the design and surrounding environment were solved in the jobsite during the work. For this reason the first applications of machine control included the product model generated by a measurement expert, a surveyor. The surveyor uses a special CAD system that has features to import 2D plans and utilize them for 3D model creation. In the CAD system missing design data is added so that the model fulfils the constructability requirements. The measurement data is exported from the CAD system to the measurement instruments and machine control.

The BIM process leads industry one step closer to utilize the design plans directly in the construction. This requires a lot of training, design instructions and collaboration between the jobsite personnel and designers to make design that fulfils the constructability requirements. There is also work to be done in design systems to reach the quality level of product models generated by the surveying CAD system. One tool for a constructability review in the BIM process is a 5D simulation of the jobsite.

PICTURE 28. Constructability verification by using 5D simulation (Halttula, 2012)

Both methods, the conventional modeling and modeling in the design phase need to be supported by the production control system. The content of a production model is presented in Picture 29. The model includes more than just 3D for the measuring purposes. The production model includes also the quality parameters, constraints and data for the project management.



PICTURE 29. Production model. Picture modified. (Manninen, 2009, 95)

4.4. Construction jobsite

The mass balance and optimized mass haul is the basic concept of the efficient jobsite. The land is shaped so that the end product would be continuous and smooth by its geometry (Picture 20). The material is hauled from one place to another according to plan. Short distances could be hauled by using a bulldozer or wheel loader. Longer distances require a truck or dumber. The mass balance of the jobsite is developed in earlier steps of the product's life cycle. The developed mass balance could be reviewed from the construction plans, such as mass charts. However, the quality of the initial measurements and other exceptions in the jobsite might have a big impact on the original mass haul plans. The mass haul optimization and planning are always done more precisely in the construction phase (Manninen, 2009; Halme, 2008, 15-27).

Mass haul design is a very challenging job because there are a lot of variables, such as the construction order of different locations, the amount of truck and machinery resources and the quality of the initial measurements. The constructed layers have the soil type as an attribute. For instance, some layers require gravel that consists of small rocks in a specified size. In the case where rock exists in the jobsite, the blasting level can be determined so that there is enough rock for the needs of the jobsite. The blasted rock could be used as is to fill a valley or it can be transited to storage, where it's crushed to gravel by using a mobile crusher. (Halme, 2008, 27-29)

The machinery (Table 1) is used to perform the cut and fill operations. Machine control systems can be used for both operations. The fill operations could be divided into two parts. The first part is filling by using untreated material (excavated in another location) and second part is to fill and compact by using the material set by the production model requirements. The production models accuracy requirement typically increases by each layer from bottom to the top. (Halme, 2008, 27-29)

Based on jobsite visits and previous research, the work in the construction jobsite can be simplified to following activities when focusing on real-time production control: (Hendickson, 2008; Halme, 2008; Heikkilä et al., 2009):

- Production Model creation and review
- Cut
  - Harvesting
  - Soil removal and loading
  - Drilling and blasting rock. Rock loading
- Mass haul
  - To the storage including possible processing of the rock
  - To the disposal
  - To its final destination in the jobsite
- Fill
  - By material type in the storage (rock, gravel type, asphalt)
  - Including possible Compaction and watering
- Installation of structures
  - Pipes, Manholes, Light poles, etc.
  - Structure logistics
- Quality Assurance and Control
  - Compliance to building requirements by:
    - Deviations between As-Built and Production Model
    - QA/QC data from compaction
    - Machine Control condition monitoring reports

4.5. Management in the Civil Construction jobsite

Overall, the management work in the civil construction jobsite is a very large topic starting from setting up the project work group and their responsibilities. The complete management work in the top level is not in the scope of this work but some general principles that apply to the complete process are important to discuss. Before the production control is possible a plan and a management method needs to exist. There are efficient management methods, such as Lean management, Location-Based Management System and Last Planner® that have a relation to the hundred years old principles, back to the days of the Frederick W. Taylor and Henry Ford (Koskela et al., 2012). It is interesting to see that the principles that have developed during the past one hundred years and have proofed their effectiveness in the other industries, such as agile methodology in ICT and Lean production in automotive industry, are very close relatives to the ones used in a modern civil construction jobsite. (Koskela et al. 2010; Koskela, 1999)

Koskela has summarized the principles improving the production activities universally (Koskela, 1993):

1. Reduce the share of non value-adding activities (also called **waste**).
2. Increase output value through systematic consideration of customer requirements.
3. Reduce variability.
4. Reduce cycle times.
5. Simplify by minimizing the number of steps, parts and linkages.
6. Increase output flexibility.
7. Increase process transparency.
8. Focus control on the complete process.
9. Build continuous improvement into the process.
10. Balance flow improvement with conversion improvement.
11. Benchmark.

I lift s few principles from the list for a further discussion. According to Toyota Production System, all activities that do not create a value to the end customer are considered to be waste. The waste reduction means that the waste of materials, time and effort needs to be minimized. Sometimes the three might conflict and then the best compromise needs to be determined. (TPS)

The wastes in the civil construction project might exist in several places. Halttula (2012) presents a table by Manninen that identifies the most crucial waste types of the Finnish construction industry (Table 3). The waste types have a waste score calculated based on the characteristics of the waste under examination. The highest waste scores are identified in the communication and documentation, unused potential of the employee and in the performed errors. Also production of the wrong product is high ranked.

TABLE 3. Waste types. Table modified. (Halttula, 2012)

Waste type	Waste score	Significance	Rate of Occurrence	Observability
Communication and documentation	328	8.0	7.0	5.9
Employee's unused potential	251	6.9	5.6	6.6
Errors	238	7.0	7.0	4.9
Production of wrong product or service	207	6.9	5.3	5.7
Unnecessary moving	201	4.8	7.3	5.7
Non-interoperate processing	187	6.0	5.5	5.7
Making-do?	186	6.4	7.0	4.1
Overload	176	6.7	6.6	4.0
Poor constructability	152	6.7	5.3	4.3
Over production	148	7.1	6.6	3.1
Waiting	146	6.0	5.9	4.1
Unnecessary transportation	144	4.9	7.1	4.1
Safety	51	6.5	2.3	3.3
Over storage	45	4.3	6.2	1.7
Others (weather, theft, vandalism)	30	4.7	4.8	1.3

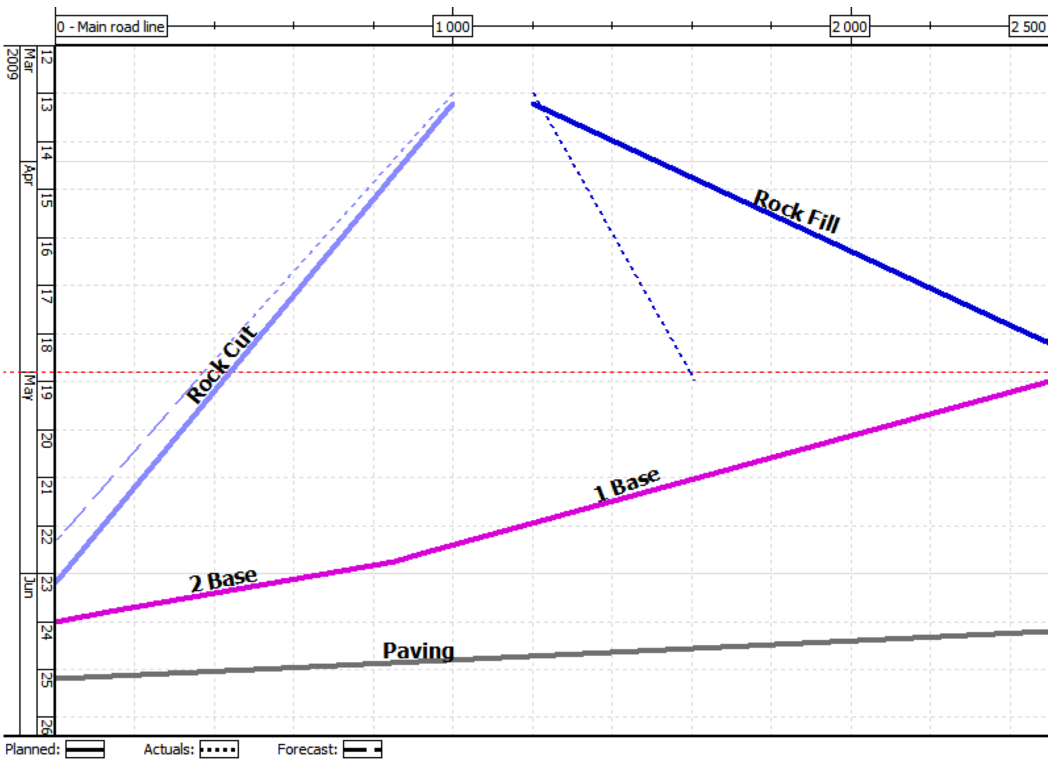
The principle for customer requirements is also related to terms push and pull. For the perspective of the construction site the push could mean that design pushes a plan for construction instead of the construction side contributing on content of the plans for receiving a plan that is usable for construction phase. In the Lean, pull is one of the main principles.

Reducing the variability means using the best-known practice for similar tasks. However, the civil construction has more variability compared to automotive business. The ‘optimal way’ cannot always be determined because the resources and their capabilities are not similar. In civil construction the task is continuously changing by location and is sometimes under Acts of God, such as heavy rain. The simplest example for reducing the cycle times in the case of civil construction is to control the amount of trucks for a specific cut or fill activity. If the construction machine or truck needs to wait for other resource the process is not perfect.

Overall, the civil construction production control system would allow benchmarking of different productivity and quality attributes. Like claimed in the old management adage: “You can’t manage what you don’t measure”, the management of the construction jobsite should be easier by using the real-time production control. The benchmarking and control data allow learning for the continuous improvement.

4.5.1 Schedule and Cost Management

The two dimensions that could be managed in the civil construction project by real-time production control are cost and time. The management also involves the knowledge of resources, the units that actually implement some part of the work. The work is divided in to different activities. The activities list of a big civil construction project could include hundreds or even thousands of items. There are dedicated personnel to handle the management activities. The activities are usually visualized in the bar charts and activity diagrams. In the road construction projects, a specific time-distance chart (also known as time-location chart) could be used (Picture 30). In this chart type the time is presented in the X-axis, usually from top to down and the station number along the alignment geometry in the Y-axis from left to right. The planned activities can be easily compared to the realized and forecasted ones.



PICTURE 30. Time-Distance chart (DynaRoad)

The art of activity scheduling could be divided into six steps (PMBOK, 2004, 125):

1. Activity Definition
2. Activity Sequencing
3. Activity Resource Estimating
4. Activity Duration Estimating
5. Schedule Development
6. Schedule Control

Activity definition and Sequencing is done in some degree during the previous phases of the project with a rough mass haul plan. Also the work's implementation plan is decided roughly during the planning phase. The virtual constructability check possibly changes the plan before construction. However, there is an initial state for the more precise schedule management in the construction phase. The resource and duration estimations are based on the knowledge from the recent similar projects. There are different methods to analyze the plan and to calculate the duration for the bigger part of the project. The most famous methods include Critical Path and Critical Chain. The basic principle in both is to link the resource allocation to the activity sequencing.

When going down from the principle level to methodologies, the Last Planner developed by Glen Ballard and Greg Howell in the 90's seems to have the most important point of view for the principles common to all modern management methods (Koskela et al., 2010). The Last Planner is a production planning system for predictable workflow. The Last Planner system is divided into five principles. The first principle is that the work should not be started before all items for completion of the work are available. Second principle is that activities should be monitored and controlled. The Percent Plan Complete (PPC) is used as a metrics tool to count the percentage of completed activities in relation to all activities. Third principle is a continuous improvement and learning with non-realized tasks. The fourth principle involves work buffers. Each crew should have a secondary activity to avoid lost production in case of exception in the primary activity. Last, the fifth principle suggests having an active look-ahead planning. In look-ahead planning all prerequisites for upcoming activities are solved and material buffers are examined. This leads to better economy due to reasonable sized material buffers. (Koskela, 2000, 191)

The great thing about Last Planner is the multiple level of planning. The big picture of the project is managed in the different level. By using a traditional method a lot of effort is wasted by managing and changing the very detailed activity plan every week. The Last Planner does care about single activity more than three or four weeks ahead. One reflection of Lean thinking is the PPC measure that supports continuous learning.

Another side of the Project management is the cost. The cost management is divided into following parts (PMBOK, 2004, 159):

1. Cost Estimating
2. Cost Budgeting
3. Cost Control

The cost estimating is an approximation of the resource cost in currency to complete the planned set of activities including the variation and risks. The cost budgeting aggregates the estimates into the activity level. This allows the cost control and measurement of the project's performance. The civil construction projects are typically very expensive and usually owner pays some amount of the work according to realized work during the project. The cost budgeting is very important for keeping the project's cash flow in the positive side. The cost control focuses to search the cause for negative or positive variance between budget and realized result. The cost control is an important part for risk control and learning. (PMBOK, 2004, 157-178)

In theory, the production rate of the construction machine could be calculated by the civil construction production control system. Also an online activity status reporting could be possible, even by automatic function. These features would create a feedback channel to the schedule control by refining the initial estimations. Schedule development would be faster due to the online data. The activities could have cost attributes and feedback channel could allow the different measures to be used, a cost, time or amount to name a few.

4.5.2 4D and 5D Tool

Based on the worksite visits one of the traditional management tools is a large base map printed to the wall of the jobsite office. Different locations are coloured meaning the level of completion or other activity. The colour adds another dimension of information. 4D-tool is capable of importing 3D plans and changing the view according to the time attribute – in to the future or to the past. The 4D tool is a visualization of a construction plan and completed activities. The coloured map in the jobsite office could be considered as a predecessor of the 4D-tool.

The 4D tool requires the 3D objects to be linked to the activities the completion status of which is reported from the field. If 3D objects and tasks are coming from the different sources the combination of two requires some level of manual work. Eastman et al. says that in building construction the 4D CAD tools have gradually moved from research lab to the construction office. I suspect same to happen in civil construction. Eastman et al. recommends looking into following capabilities when considering an investment to a 4D tool (Eastman et al., 2008, 291):

- BIM import capabilities, such as object's geometry, name and UID
- Schedule import
- Model version control
- Model update and merge capabilities
- Reorganization of data

In a project where a long continuous 3D object, such as highway, needs to be imported together with the activities, the integration is not straightforward. The same applies to the cost. If you considerer a relatively small installation, a rigid component the price of which can be determined unambiguously, the price of the complete assembly is relatively easy to calculate by its progress. In the case of a continuous 3D object, the cost of the unfinished, constantly changing surface is harder to determine.

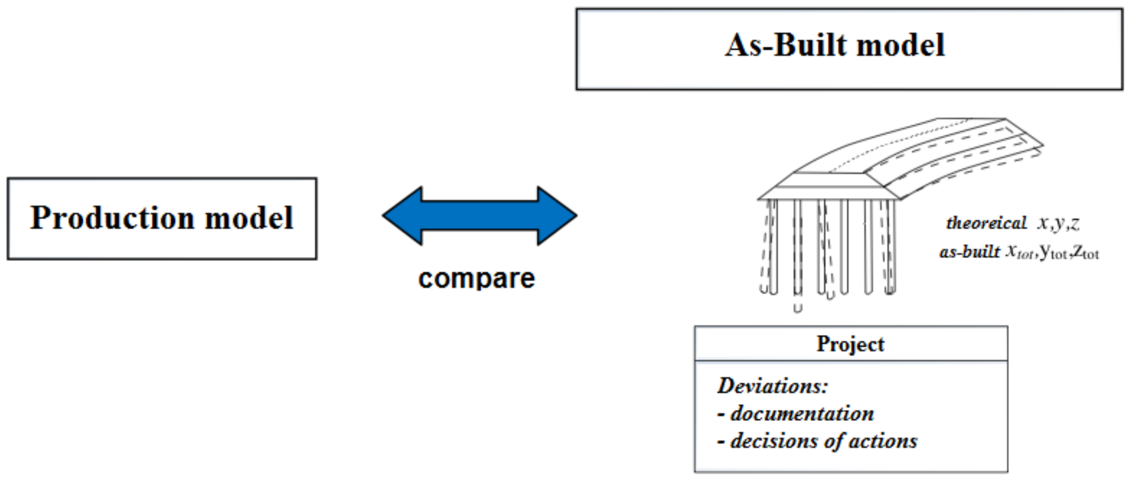
The simulation of the construction order can be used to verify the constructability. This task should be done in the design development step. The same model, once created, can be utilized in the jobsite. Increased synergy for creating the model reduces its price and ROI.

4.6. After construction phase

There are always surprises when developed design data is applied to production. The inaccuracy of initial measurement can be seen when rock is exposed after soil is removed. In these cases the jobsite needs to handle the exception, usually without the designer to make revised plans. The implemented work that differs from the designed one is measured and updated to the as-built model. If conventional as-built rules are followed, a lot of manual measurement needs to be done by fixed steps along the geometry (for example all side lines every 20 meters).

The owner usually requires a drawing with measured coordinates for underground structures, and other installations (Pelkonen, 2012). In some markets the BIM process might lead to more intelligent forms of As-built data, but it shall also be possible to get the data out for implementing conventional drawings.

The as-built model for a maintenance phase could be compiled from earlier virtual models, onsite measurements, and quality data. The content of the as-built model is presented in picture 31.



PICTURE 31. As-built model. The picture is modified from the source (Manninen, 2009, 96)

The maintenance model includes relevant data from the As-built model together with condition monitoring and maintenance instructions. The model including the condition monitoring data works as an initial data for road rehabilitation projects. The maintenance model includes the realized cost of the maintenance work. This data can be used when calculating the effect of the used design option on realized maintenance cost. The management principle of learning can happen at all levels.

4.7. Conclusions

The BIM process is a great enabler that increases the level of autonomy in the civil construction jobsites. The BIM has a change to remove the polarization barrier between the contractors caused by the different skills in utilization of automation by using drafting centric design data for construction automation. As seen already with the advanced contractors the increased autonomy level leads to a need for the production control system.

The roles of the stakeholders do not change a lot due to a BIM process and automation in construction. However, the need for new skills and collaboration increases drastically. The key player in the construction site is a surveyor or a model coordinator, whose expertise is to maintain the BIM during the construction phase.

The industry has adopted new management methods for conventional civil construction and they should be carefully examined when creating requirements document for the civil construction production control system. During the study I discovered the versatility of different management methods, principles and concepts existing today. Even thought the one step of the project controlling would be automated, there is still a lot of space for non-automated human thinking in the different arts of management.

The 4D tools have proved their importance in the building construction industry. The 5D tools are already usable for checking virtually the constructability of the structural civil engineering project. The continuous 3D-objects such as roads are complicated to divide into practical parts. Novel 4D-5D tools are required with ability to integrate to production control and continuous models. The efficiency increase by connecting the machine control system in the jobsite and the 5D model in the office is waiting to be unleashed.

5 PRODUCTION CONTROL SYSTEM BENCHMARKING

The life cycle of the product management is a familiar topic in many different engineering industries. The very same collaboration needs for the design-manufacture phase exist together with a need for the production control. This chapter discusses the current state of the art in the field of production control and collaborative tools in the industries of building construction, mechanical engineering and civil construction. The tools discussed support the principles of the Lean manufacturing aiming for the waste reduction to achieve the more efficient manufacturing and improved quality.

5.1. Information model and Production in Mechanical engineering

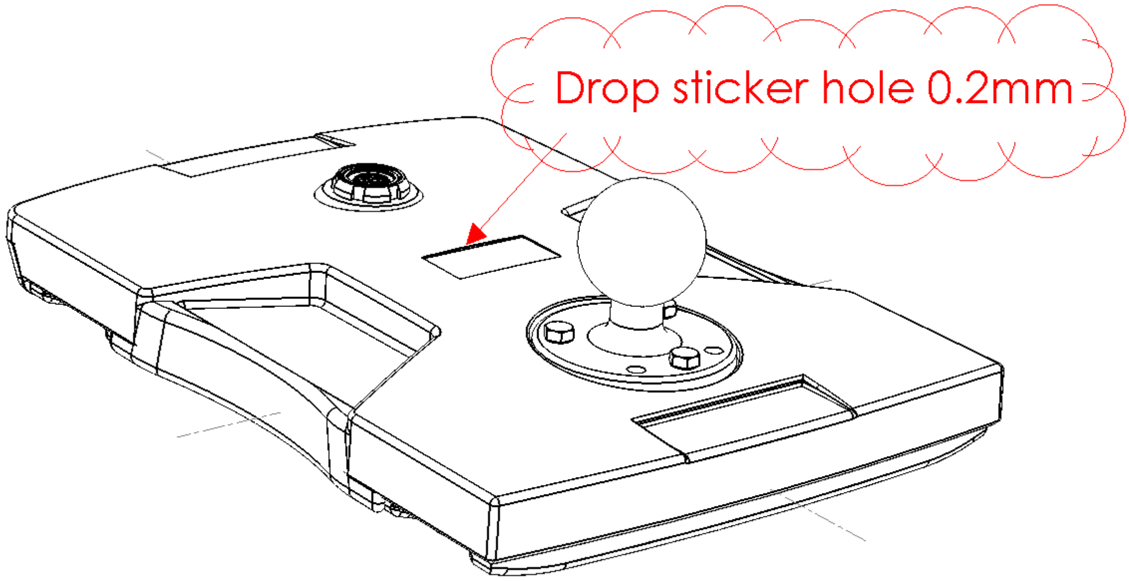
The life span of a mechanical object could easily exceed the life span of the design CAD system. Therefore an open format is required to ensure the maintenance of the product during the years when the CAD systems evolve and change their form. In mechanical engineering the first data exchange format between the different CAD systems was published as standard in 1980 and was called IGES. The format has its roots in the United States Department of Defense who set the requirement in 1988 that all weapon contracts need to be delivered in the electronic form such as IGES. The format allows the data exchange of the circuit diagrams, wireframe, freeform surface and solid modelling representations. Mechanical engineering shares the same problem as the geometric design in the civil engineering. The continuous dual sloping surfaces that have rule dependencies on other geometries cannot be exported in the IGES format without calculating the resulting model to a freeform object. Freeform could be compared to the TIN technique discussed in the chapter 'Digital Terrain Models'. (IGES)

In mechanical engineering the Computer-aided Manufacturing (CAM) is used to create a tool path code for a computer controlled machine, such as multiaxis milling machine. The target is, likewise to civil construction, to minimize the waste, reduce the cost and improve the quality. The automation level in making mechanical products is in some cases very high. The autonomous machines can be closed to a safe place to perform their work. The most modern factories can operate autonomously for days unmanned. If there are no exceptions in the process the productivity can be simply calculated. The problems in the factory are focused on the on-time supply and delivery of material and products. The adaptive process control is a feature of the unmanned production system. (Fastems)

One notable feature of the mechanical engineering is the systematic use of the quality attributes, such as accepted tolerances and flatness requirements. When parts are manufactured, a certain amount of them is verified to fulfil the requirements set by the designer. These kinds of quality attributes also exist in the requirements of the civil construction project but the data is not exported within the production model. One reason for this could be that general quality requirements are common knowledge and have less variation to ones used in mechanical engineering. The product in the construction site is verified by using a similar method to mechanical engineering. (CAM)

In mechanical engineering the project has similar collaboration and project life cycle management needs to ones in the construction. In mechanical engineering it is very common to use a PDM system as a project data repository. The PDM system includes the drawings and the CAD models among the other product life cycle documents. Such system can be compared to a version control in software engineering. In civil construction the utilization of the PDM system does not seem very popular. (PDM)

There is also a need to communicate with the customers, subcontractors and others outside the availability of a specific PDM and CAD systems. The easiest way to review the designed model is to use a tool like eDrawings by Dassault Systemes S.A. The designed model could be embedded to an executable, sent by e-mail, and opened for viewing by the customer or other project participant. The tool has features to view the model in 3D, view cross sections, measure the object and comment the model by adding the notes (picture 32). One purpose for the review is the virtual verification of the constructability of the model. This communication method has proved its efficiency in several mechanical projects done for Novatron Oy. (eDrawings)



PICTURE 32. Dassault Systemes eDrawings.

Another type of a collaboration tool is a data management system, like Buzzsaw by Autodesk or M-Files. These tools are closer to revision control systems used in the software engineering. The cloud service could be mapped to a folder or to a drive and data could be synchronized between the workgroup automatically. The data ownership and user permissions could be flexibly set.

5.2. BIM and Production Control in Building Construction and Structures

The building construction business has created the term BIM and is the biggest reason for the civil construction BIM activities today. The BIM is reality in many parts of the business, in big buildings, bridges and facilities to name a few. The design systems have integrated cost and scheduling abilities. The building construction BIM also interfaces to the civil construction side. The bridge is a typical structure that needs to be adapted in to the geometry of road or track construction projects. Usually the two, the road and the bridge are designed in the separate CAD systems because the modeling practices differ totally. The one uses geometry and the rules while the other is modelled by using a solid. However, the interoperability between the two worlds is required. Some applications exist where the road geometry can be imported to the bridge modeling purposes, e.g. Tekla Structures and Tekla Civil. Note that Trimble Navigation acquired Tekla in 2011. (Heikkilä, 2008, 23)

The interoperability is far ahead of the civil construction due to the open IFC standard. The standard is nowadays developed by the buildingSMART organization. There are already owners in Denmark and in Finland who have set the use of the IFC standard compulsory in their projects. This could be compared to decisions made by U.S. DoD with mechanical engineering. The owner seems to have the best possibility to lead the industry further in the product life cycle matters. (IFC)

In the building construction the similar free viewing tools are available as there are in mechanical engineering. Tekla BIMsight is one of these tools. The tool enables the easy contribution and the faster decision-making. One can login to the cloud service and review the model by using a mobile or other computer device. The open model is more intelligent in the building construction than in mechanical engineering. The components have features such as material, schedule and also other properties needed by the construction company, part fabricator or anyone else in the building project. The latest applications introduce the utilization of the Augmented Reality. One can go to the field, exactly to the place where a new building is designed and view the environment including the designed building (Vianova iPad Viewer). There are also modern 4D tools available that allow a virtual model based examination of the progress and future activities of the project over time (Eastman et al., 2008, 228). Some tools include also the fifth dimension (5D) that is considered as a cost.

Eastman et al. lists the following process and technology trends for BIM (Eastman et al., 2008, 289-291):

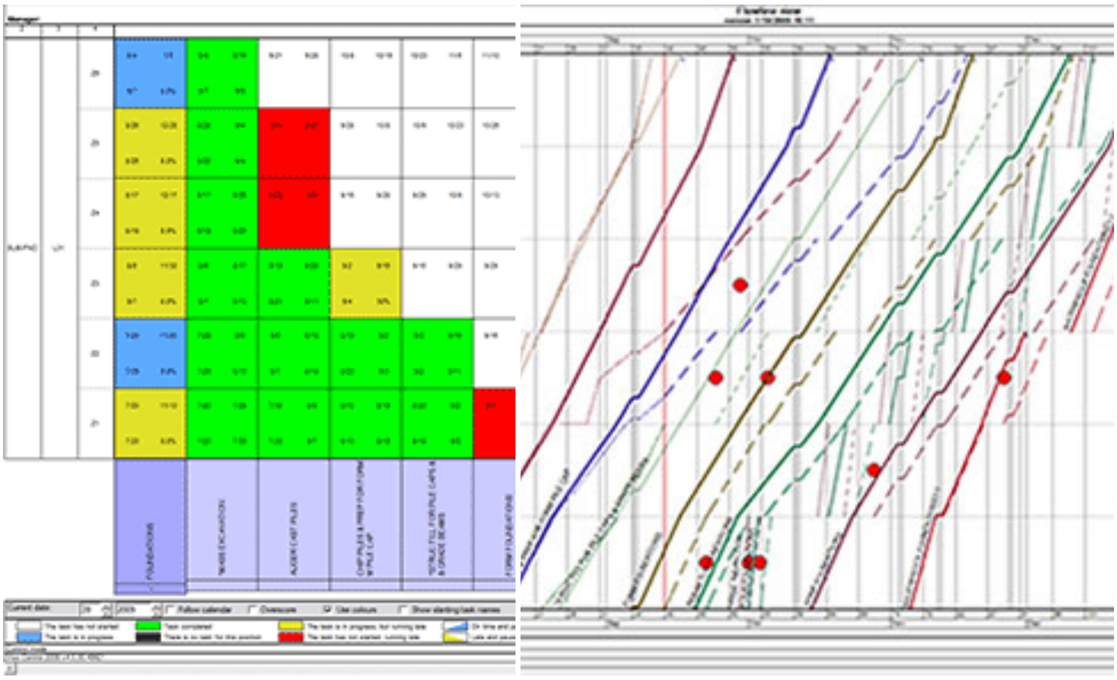
- The sophisticated owners are demanding BIM and changing contract terms to enable its use. In civil construction the rules and processes that allow owner to move into BIM are under development.
- The new skills and roles are developing. In some part of the processes 30-40% productivity gain has been measured. The drafting staff could be downsized, but more effort is required in the modeling phase. Similar need is followed by BIM in civil construction. The need is partly triggered by automation in construction.
- The pioneering contractors take the corporate-wide advantage by re-engineering their process.
- The green building is increasingly demanded. The energy needs can be modeled by using the BIM tools.

- The automated constructability. Tools are also available for the civil construction.
- The construction management functions are being integrated to the BIM tools.

One note presented by Eastman et al. proves that BIM process in the building construction is taken seriously; the construction contractors in Europe are beginning to integrate BIM tools with Oracle ERP system and model server technologies (Eastman et al., 2008, 290). Such integration means that the BIM process is becoming an important part of all of the actions in the company. The building construction BIM is ahead of the civil construction. The leading trends of the building construction side need to be looked at carefully and adapted to the civil construction side where applicable.

The production control tools for buildings include the Vico Production Controller software. By using Vico Production Controller the supervisor of the jobsite can control the schedule with a Location-Based scheduling method. The Location-based method is explained in detail in the Doctoral dissertation of Mr. Seppänen (Seppänen, 2009, 24-46). The logic is not easy to explain shortly due to the complexity of the approach. The basic idea behind managing the crew location seems to be that the different sub-contractors or crews should not interfere each other's work in the same location at the same time. The locations have tasks and quantities. The task durations are calculated based on the quantities (units of work), resources and so called consumption rates. The consumption rate indicates the time that a resource takes to produce one unit. In short, this is the efficiency of the resource. The system also takes a lag, called buffer, into account. The calculation uses a tuned Critical Path Method. Seppänen says that: "Location-Based Planning attempts to achieve feasible schedules with acceptable risk". (Seppänen, 2009, 32)

The team members update the actual realized status of the activities in to the system on a daily or a weekly basis. In the controlling phase, the supervisor has tools, such as Production Control Chart and Look-Ahead Flowline schedule (Picture 33). The Production Control Chart is an interface to update the realized status by the location. The Look-Ahead Flowline schedule is used for comparing the realized production rate (dashed line) to the planned one (constant line)



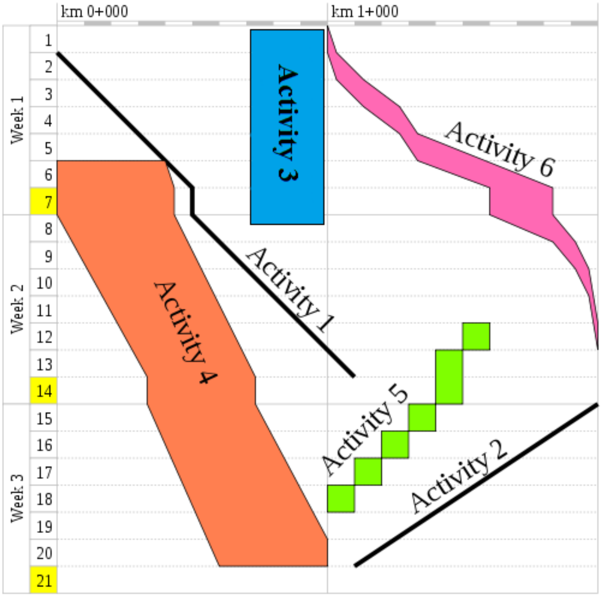
PICTURE 33. Production Control Chart and Look-Ahead Flowline by Vico Software (Vico)

Another aspect in the Production Controller is a promised and realized productivity rate of the subcontractor. The productivity rates are stored and could be used as an initial value for a cost calculation of the new project. The system also has capabilities for the data mining and has different reporting options. The reporting options include different views integrating the cost of the project, time, resources and their location. The advantages of Location-based management should be considered also for the horizontal construction. Trimble Navigation Ltd acquired the Vico Software, Inc. in November 2012. (Vico)

5.3. Production Control in Civil Construction

According to the jobsite visits the most important things to control in the civil constructions jobsites are the mass haul plan and the actual realized status of the worksite activities. If the worksite activities are delayed and the project is not finished before a due date, typically a penalty must be paid for the exceeded overtime. The penalty is usually in the range of a few thousand Euros per day. If the realized mass haul does not correspond to the one in the plan, the problem could be even bigger. The mass haul makes the most of the cost in the construction jobsite. Moving masses in a non-optimal manner may lead to the costs that exceed the profit margin of the project. There are many project management tools for project scheduling and to an activity follow-up. The software packages that include the location-based methods are preferred in the road construction jobsite. The time-distance chart is not feasible when created in the Excel spreadsheet. The time span of the view can vary from minutes to years depending on the current needs. This detail could lead to a significant level of manual work to maintain in the spreadsheet. Therefore the software packages, such as Artemis Planet, DynaRoad, LinearPlus, TILOS or Vico Software are used. There are also small companies who offer the tools for the time-distance chart creation out of a Gantt chart created by the conventional scheduling software such as Primavera or Microsoft Project. (Time distance diagram; DynaRoad Wikipedia)

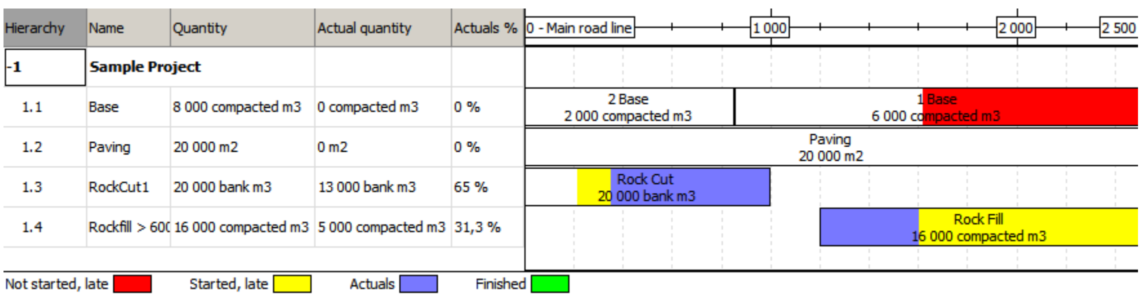
The location-based chart has more features than previously discussed linear activity in chapter 4.5.1. The main idea of the location-based method is to prevent the work crews from occupying the same location and disturbing each other's work. The linear activity where a line presents a continuous single activity in the time-location relation is the main functionality of the time-distance chart. If a single location is occupied for a significant period of time, say for the deep stabilization purposes, the activity is presented as a rectangle (Picture 34, activity 3). If the activity is continuous and the time spent for each location is known the paralleogram is used (Picture 38, activity 4). If the attributes of the location reflect to time spent on a specific location the non-linear line is used (Picture 38, activity 6). A soil removal or other mass replace activity would potentially be a non-linear line. The weekends when the project will not progress can be seen in picture 38 with a vertical shift on each activity. The realized status could be visualized in the same chart by dotted or transparent objects. (Time distance chart)



PICTURE 34. Object types of the time-distance chart. Picture modified. (Time-distance chart)

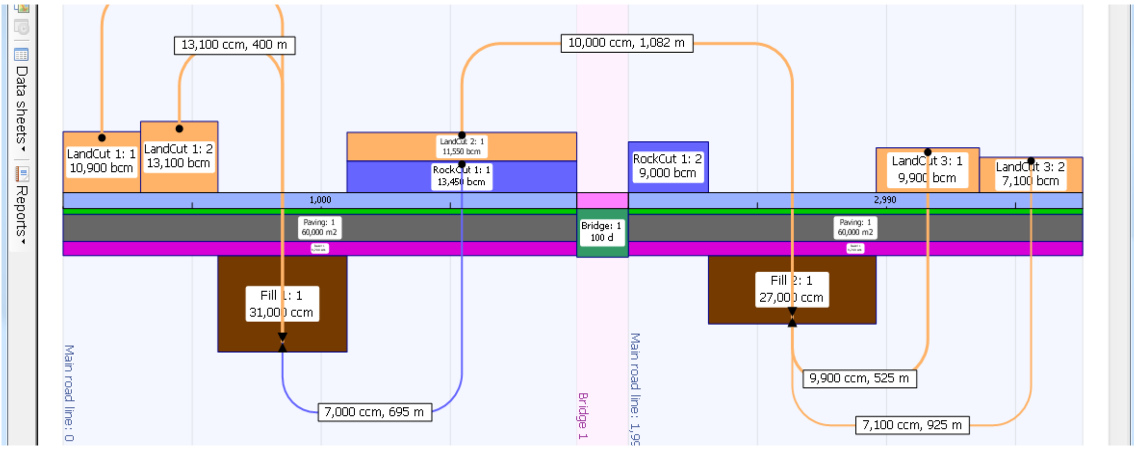
The linear activities are simple to control visually. If the realized status is noticed to be behind the schedule and the corrective action is done, the magnitude of the action, such as resource update, could be checked visually when the new realized status is updated. (Söderström & Olofsson, 2007)

DynaRoad Oy is a company in Finland that is focused on the location-based planning and the control in the civil construction. A time-distance chart could be used for examination of the progress of the project. Their specialty is that they can plan, optimize and control the mass haul process of the road construction project. The key features include: Actual vs. Planned production rates, Actual vs. Planned mass haul, Remaining amounts of cut and fill, Control chart and reporting options by actual mass flow, workflow and completion degree (considered as PPC). The control view offers quick review on the status of the project (Picture 35).



PICTURE 35. Control view (DynaRoad).

Another very practical view is the mass-view plan where the cut and fill positions are presented along the road line. The actual earthworks can be seen as arrows from one place to another (Picture 36).



PICTURE 36. Mass haul view (DynaRoad).

The DynaRoad is claimed to be a very powerful planning tool. The downside in the DynaRoad is the controlling part where the automation for a realized mass haul seems to be missing. The conventional way to track the realized mass haul is based on a hand-written document that is manually entered to the system (Lippo, 2007, 8). A Topcon Positioning Systems purchased a significant share of DynaRoad Oy in 2011.

There are a couple of papers available regarding the real-time mass haul management. The first paper is from 2007, where a system was built for a big Finnish civil construction company Destia. The system was based on a research project “LATO” by VTT Technical Research Centre of Finland and was funded by the Finnish Funding Agency for Technology and Innovation. The goal was to automate the manual document-based workflow. The document-based workflow introduces the typical data to be collected: date, driving distance, time to load, time to unload and material type. The document-based data is then entered to a mass haul system or to an Excel spreadsheet. The manual documents could be different between subcontractors and could be filled by a different kind of data. The lag for the results could be up to a month and therefore the conventional method is hardly usable for a real-time control of the jobsite. The cost is calculated by the total mass volume and the driving distances or simply by using a unit price (Euros/hour). (Lippo, 2007)

The new system utilized mobile phones for the data acquisition. The mass haul data together with the job and task identifiers are transmitted in to the server. The path of the truck or dumper can be seen on a map. The goal was that the system would generate a daily report including the following data: mass haul by material, driving distances and total cost. It was considered important that the supervisor should manage the fleet in person without using the system for the purpose. The results were positive. The truck drivers accepted the new technology with ease because they don't like the conventional document-based system either. The only problem back in 2007 was the size of the UI in the mobile phone. That should not be the case with modern mobile technology. (Lippo, 2007)

According to Halme, the errors in the designed mass balance calculation caused by the uncertainty of the initial data could be handled by using a real-time mass haul data. When the soil is removed and the underlying truth about material is exposed, the new information could be collected by a machine control system and the data is available for the supervisors, surveyors and designers. The mass haul plan could be dynamically re-planned. In the conventional document-based method the error might not be noticed in time. (Halme, 2008, 19)

Halme presents a model where the production models work as a job instruction for the operator of a machine control system. The as-built data is reported to the database. The truck driver receives the instruction for mass haul operation. All mass hauling is reported to the database. The production models, work plan and the mass haul optimization are always revised if either one of them faces a change. The change could be caused by a discovered mass haul exception due to the errors in the initial measurement or a change in the work plan, in the resource or in the production models.

The supervisor would be able to see the time-distance chart where the planned schedule and the realized degree of completion of activities could be read. If the storage amount for the material is relevant for the task, it is also shown in the chart. The operator of a machine or the driver of a truck can request the new activity or secondary fallback activity from the server. (Halme, 2008, 51-78)

Another option for the realized data is to track the work machine instead of a mass haul process. Navon et al. introduced a model where the horizontal position of the work machine is monitored and converted to control information such as progress, productivity and quantities. The older model from the previous research of Navon et al. used a Work Section. The work section is an area that is divided from the continuous work, such as a road in to the smaller controllable units. The size of the work section was determined by time (one day). The previous research included field experiments where the different activities were compared between ones produced by the Work Section system and manual measurements performed by the researcher. The conclusion was that the work could be measured in an accuracy range of 1 to 11% if the work was done according to a plan. So the results are depending on the actual work, if it is done like it is planned or not. The new method introduced the use of an algorithm to determine the work area dynamically. They tested three different methods for area determination varying from +166% to +15% in deviation to the actual work area. The time consumed in one location, say a grid of one by one meter, is relatively easy to determine. The problem is to exclude the locations automatically in the post-processing where the machine is moving without actually performing any work. (Navon et al., 2012)

However, by using the intelligent production model and a machine control system a lot more information is available as an attribute to the location of a machine. The identifier of the continuous geometry, such as road is available together with the knowledge about the construction layer under work. Also the deviation between a tool of the machine and the production model are known. These attributes combined to the centimetre level accuracy allow more precise determination of the performed work and its performance. Another advantage is the UI that can be used for the human input about the status of the work.

Another related technology to the management side is the Kuura system developed and distributed by the Hohto Labs Oy. The Kuura system is integrated to the Novatron Vision 3D machine control system. The features of Kuura include: position of the fleet and production models on the map, data exchange between the machine control system and the service and activity reports of the fleet. They also offer a mobile solution where the supervisor on the site can see his or her own location and the location of the fleet in respect to the production models. The most advanced feature is a cross-section view that shows the actual cross-section of the road in the selected construction layer in respect to the terrain model. (Kuura)

A Novapoint VirtualMap is a 4D/5D tool developed by the Vianova Systems Finland Oy. The VirtualMap software could be compared somewhat to the eDrawings discussed earlier; it is used to visualize the 2D/3D data. The Virtual map reads in the design models in various design formats, such as DWG, LandXML and DGN. The virtual model is mainly used for the decision-making, integration modeling and for clash detection. Also various other possibilities are available, such as a traffic light testing, analyzing of an environmental impact of a windmill park and the calculation of a solar power on a rooftop. (VirtualMap)

5.4. Conclusions

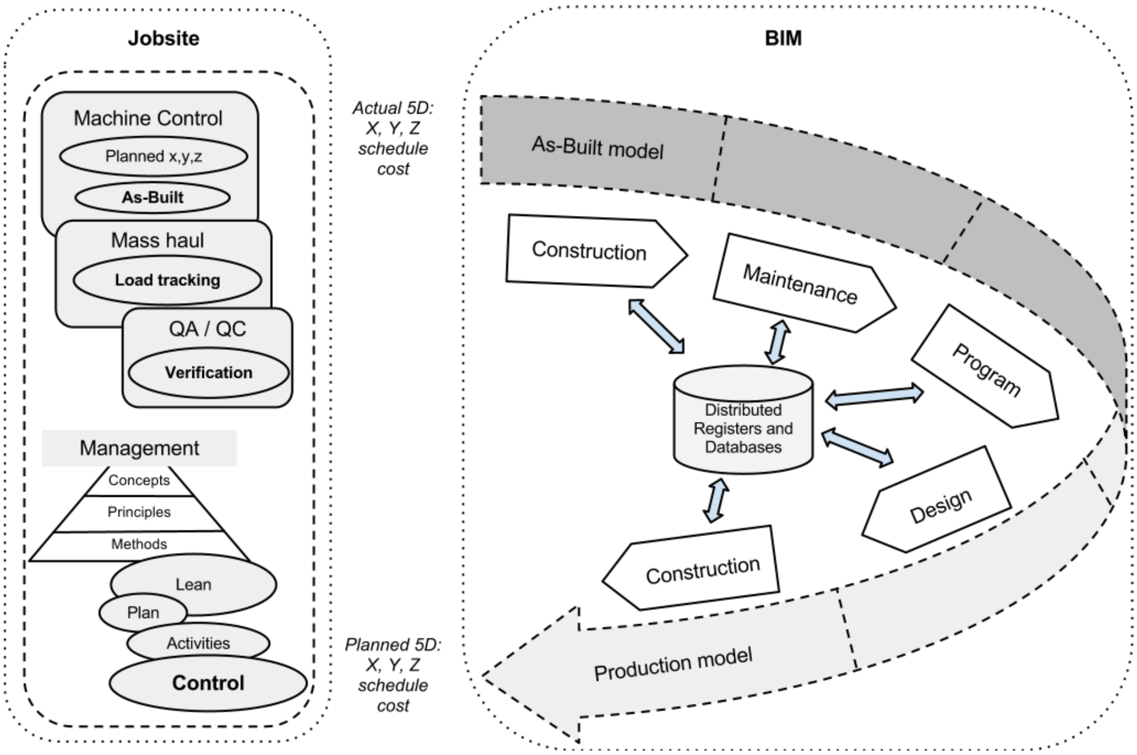
The BIM changes the civil construction industry. New skills and roles are required. Most of the product modeling shifts a step back from the jobsite to the design office. More work is required in the model integration and the amount of work for the coordination and communication to the different stakeholders increases. One simple communication method could be a simple note technique familiar from eDrawings.

The production control is not trivial in the civil construction when compared to building construction and mechanical engineering. The two compared industries have products that can be typically designed and built without an intelligent, rule-based continuous data model. However, also in mechanical engineering the dual curving model is complicated to shift from design-to-design. The complexity of the civil engineering product model has slowed down the progress of BIM process for civil engineering. The intelligence of the production model is not the issue in the construction phase. Actually, the less intelligent data is simpler to interoperate between the different measuring instruments, such as surveying field controllers and the machine control systems.

The current state of the production control in civil engineering includes the tracking of the mass haul, tracking of the machine control systems, model viewers in 4D/5D, web services for data collaboration and field instruments for helping the daily life of the supervisor. The plans and schedules are controlled, sometimes with the help of an intelligent software package such as DynaRoad. The most relevant chart viewing the state of a project is a time-distance chart. The integration between the sub-systems is missing and there is room for improvement in the real-time control.

6 SUMMARY

This work has two different domains, the BIM process that is a conceptual idea and the jobsite that is practical real life (picture 36). The BIM process is an intelligent way to utilize the data from different data owners when moving from one phase to another in the life cycle of a product. The idea is to transfer the relevant product data digitally in a computer readable form. The product data can be distributed to the databases and shared by API. Or the data could be transferred in a conventional manner, by using a data exchange file format. I encourage the people involved in the BIM development to determine the level of intelligence between the phases since the most intelligent data does not always lead to the best level of data utilization. The more intelligent design leads to virtual constructability examination by using the clash-detection. The clash detection finds the theoretical problems between the different design models before the construction phase.



PICTURE 36. 5D BIM goes to the jobsite

The jobsite domain interfaces to the BIM world by receiving production model data, preferably in the 5D form containing 3D model data with schedule and cost. The project managers and supervisors manage the jobsite. The management, in the scope of this work, discussed only the schedule and cost management. The management sets up the activities for the work crew. Every work group should have a backup activity in the case of lack of materials or other exception. The activity could be for example an earthmoving operation where one excavator cuts the soil and loads it on the truck. The truck drives to the location where another work machine needs the material for a fill task. The efficiency of the work machines can be monitored and the schedule can be updated by the realized status.

The civil construction jobsite is unpredictable by its nature. The jobsite has always exceptions to the work plans due to errors in the initial measurements and therefore the performance can never be perfectly estimated. In the production control part the deviations between the planned and realized status are examined. The efficient production control requires the real-time realized status information. The production control could lead to the correction actions where the plan, schedule, resources and models could need an update. The correction actions are not bad as long as they are done in the early phase.

Lean thinking or its derivatives should be utilized for the production process. All processes should be under constant improvement by using the benchmarking allowed by an automated system. The most significant type of waste should be removed by optimizing the production process.

The production control in the jobsite is not possible before following prerequisites are set:

1. The digital work plan and the schedule are available, preferably in a time-distance form.
2. The planned cut and fill tasks have an up-to-date production model for machine control.
3. There is a status feedback channel that corresponds with the planned work. The automation of the feedback channel is preferred.

The output from the jobsite back to the BIM world is called an as-built model. During the work, the QA/QC process verifies that the quality requirements of the product are set. If the deviations between the planned model and the actual, realized model exceed the quality requirements, the case is discussed with the owner of the product and corrective actions are decided. Controlling the condition and the accuracy of the measuring instruments, such as machine control systems, the amount of manual QA/QC can be reduced. At the end of the project the as-built data is interfacing to the maintenance model.

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