On-machine Control and Documentation Systems for the Quality Management of Roads

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Abstract— **Quality management of the construction process is finding its way into the construction industry and authorities. with the goal of higher profitability, increased efficiency, reduced cycle-time, decreased call-backs and warranty work, and increased customer satisfaction. To reach a total quality management throughout the whole lifecycle of a construction (consisting of the steps 'planning', 'design', 'construction', 'operation and maintenance' and 'deconstruction'), all the single steps have to be connected. As each construction is an unique, it's difficult to get key figures for the quality assessment, hence the quality of the process itself has to be assured.**

To acquire quality figures, the people and machinery involved in the construction process and the process itself have to be well described. Moreover they must deliver process values that allow the judging of the quality achieved.

In other words, the issues addressed and to be solved by quality management in construction can be dubbed as "Information Management on construction worksites result in higher quality". This implies

- the role of building and construction as a product

- the need for initiative of the involved industries (contractors, construction machine manufacturers and IT-business)

- owners of infrastructure that define quality standards and agreements on transfer of relevant information between processes and acting players.

The data acquired on a machine can be divided into three types: machine data, process data and project data. Machine data consists of measurements close to the machine e.g. engine speed, oil pressure, fuel level. Process data is more related to the construction process. Considering a road paver for example, process data would consist for instance of layer geometry (thickness, width) and material values (amount, temperature). Project data comprises data acquired by all machines involved in the construction process. In the example of road construction, this includes among other things road geometry, number of compaction passes of all rollers and density measurements. Modern construction equipment gathers machine and process data to a certain extend. To acquire project data, all involved parties have to exchange data. This data exchange has not been established yet, although noteworthy attemps were undertaken. The full article will describe the means to provide the required data and information technology that cope with the requirements of quality management in construction. Within this part the specialities of road construction and new products and processes enhancing the TQM are presented.

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Index Terms— **Automation, ISO, Life cycle costing, Quality assurance, Quality control.**

I. Introduction

After the construction of a building, a contractor must provide repairs without any further refunding due to warranty. In general, the usual warranty period for conventional contracts is a few years, and the occurrence of failures in construction in this short time span is relatively low.

As more and more public construction jobs consist not only of the construction itself but also of the operation of the building for a longer period (typically ten to twenty years), the contractors are increasingly interested in a higher quality of their 'product' as it saves costs in the long run.

An example can be shown in road construction, where a contractor has to warrant the functionality for twenty years. If the maintenance intervals can be increased from 5 to 7 years due to an increased quality, one repair work can be saved, such cutting costs substantially.

To provide a higher quality of a building, the achieved work has to be surveyed and analyzed. Especially on construction machinery the monitoring of process data is easy as they can be equipped with sensors and controllers to record the relevant information for later analysis in the office.

Compared to other industries, the construction industry is exposed to special difficulties. Especially delays are a challenge to quality and project management as they are hardly predictable (e.g. bad weather).

II. Quality Management in Construction

Construction firms are more and more focussing on improving the quality of constructions and their processes. Especially the increasing number of functional and public-private-partnership contracts forces the firms to produce high quality constructions and buildings as an extended service interval can reduce costs significantly. To be able to measure the quality of a project, quality management in construction has to be established.

The possibility to influence the final costs of a construction project decrease with the advance of work (see fig. 1). At the beginning of a project

A. Special Conditions in Building and Construction

It is difficult to acquire operating figures for quality management in planning and construction, as construction projects are always unique ventures. The quality of the construction *processes* is easier to monitor, as the processes are repetitive or at least similar. To reach a high quality, the process quality has to be watched and assured [4].

Construction processes are often influenced by a large number of external influences which make their duration and cost hard to plan. Three types of delays can be distinguished:

1) Inadequate specification

The specification can be to short or even wrong. The identification and correction during the construction process allows the contractor to request compensation for the additional effort.

2) Intervention by the owner

Occasionally the owner makes changes to the planning even after the conclusion of the contract. In this case, the requested construction work differs from the calculated effort. Such interventions lead to additional claims of the owner.

3) Disturbance of the construction work

The construction process as planned and calculated by the owner can be changed by external factors. Such disturbances can be bad weather, the delay of work of pre- or sub-contractors, missing planning material.

As such interruptions and delays cannot be foreseen, construction firms have to file amendments to the original contract in order to receive compensation for the additional costs. The delay of a task in a project can lead to the delay of the finish date of the whole project if the task is part of the critical chain of the project.

Contractors are interested in minimizing the number of delays in projects as they make the project difficult to plan and to cost out.

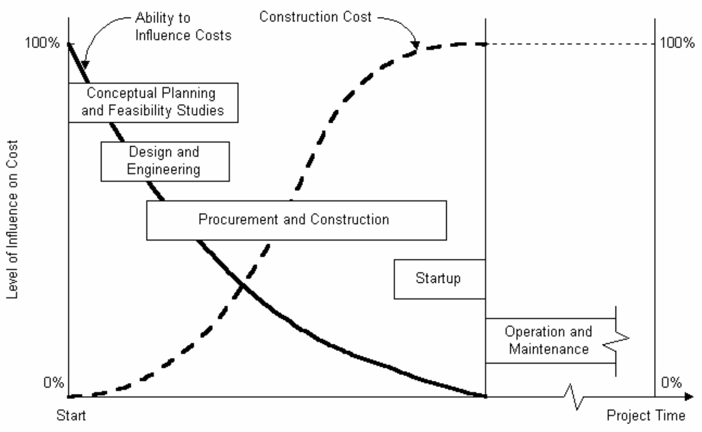

Fig. 1. Ability to Influence Construction Cost Over Time [3]

B. Requirements for Functional Contracts

Most of the construction business is far away from any market condition where the user-demand determines the volume of investment. This applies particularly to the road construction business where the authorities can only distribute the means supplied by the political decisions who themselves are dependent on fiscal constraints. Frequently the mentioned monetary constraints are subject to change for a bigger road construction project as the fiscal planning is versatile. Moreover, public budgets are getting increasingly tighter, also when meeting convergence criteria of the European Union during times of an economical depression. Increasingly there is a substantial gap between required infrastructure measures and financial possibilities and sometimes a missing will of the public owner. Only in Germany, this gap causes already today a waste of about 14[1] billion litres of petrol by cars trapped in a jam.

On the other hand the practice of tendering the construction measure, contracting it and after accomplishment of the initial construction the road is transferred to the public authority, causes the effect, that road construction measures are conducted in the way where the contractor produces the road according to a list of requirements mainly consisting of geometrical and physical values like layer-thickness or density put up by the authority. Usually the control of these requirements is carried out by drilling and evaluation of cores. This always implies the probability that failures and defects do not reveal within normal control of a construction measure. After a short warranty time, the following operation and maintenance phase of the road - in particular its economical risk - is back in the hand of the owner.

Since the beginning of the nineties of the past century, the contractual relations between the asphalt contractor and the road authority is getting more and more attention. A shift from a traditional contract system as described above, where the client specifies the required construction and materials in detail to modern contract forms as the functional contract and DBFO-contracts (Design, Build, Finance and Operate) where the contractor is granted much more responsibility and liability. It is expected that this will stimulate contractor innovation and cost effectiveness of road pavements. The contractors can be paid either by the authorities (who themselves generate the incurring cost by tolls) or are given the right to obtain a toll fee from the users of the road.

Within the functional contracts the contractor adopts to the point of view of an owner as he obtains responsibility for the built infrastructure. By adopting the viewpoint of the owners, one can focus its attention on the complete process of project management for constructed facilities rather than the historical roles of various specialists such as planners, architects, engineering designers, constructors,

[1] Verband der Automobilindustrie 1998

fabricators, material suppliers and others. To be sure, each specialty has made important advances in developing new techniques and tools for efficient implementation of construction projects. However, it is through the understanding of the entire process of project and quality management that these specialists can respond more effectively to the owner's desires for their services, in marketing their specialties, and in improving the productivity and quality of their work. [3]

C. ISO 9001

Responding to the growing demand for process oriented project and quality management and the needs of other industries in the global marketplace, the International Organization for Standardization (ISO)—a global federation of national standards organizations based in Geneva, Switzerland—has developed the ISO 9000 series of quality management standards.

Within the construction industry, public and private owners are requiring the construction and design professionals to have a proven quality management system as a standard business practice. To demonstrate their clients that they are committed to meeting project requirements, contractors are searching for new techniques that will enhance the quality of their performance efforts.

Additionally, the broader use of functional contracts creates a demand for better documentation of performed work. In response to this growing demand, the parties involved in the road construction and process, designers, contractors, residential engineers and authorities implement quality assurance mechanisms following the ISO-9000 scheme.

1) Quality management within public authorities

Not only the construction industry - in particular the construction material producers - are becoming more and more aware of the advantages to improve their performance by ISO 9000 certification when bidding for a tender: Quality assurance systems are increasingly becoming part of the authorities: Observation by public, the strive for a lean public administration, the increasing pressure of cost, the demand for sustainable infrastructure measures and last but not least the own will of public services to steadily improve its performance render introduction of broader quality management systems. The approach of ISO 9000 is process oriented and meanwhile quite liberate regarding its implementation to different institutions. Therefore it can be tailored to the demands of the authorities involved in the construction process.

Exemplarily the Hessian Road Authority is mentioned, as they were undergoing ISO-9000 certification for their whole process management[2]. During the past years, the Hessian authorities were implementing quality assurance systems following the ISO 9000 scheme [4]. It has been adopted to both the internal requirements and to the needs of the various clients of a public road authority. Clients are typically the contracted enterprises for road construction, maintenance and refurbishment, they shall profit from the quality management efforts of the authority. Moreover the clients of authorities are the federal and state governments and the adjacent offices and authorities.

Heart of the quality management is a quality manual which is structured according to the processes. The quality instructions follow this process break-down and have to be improved steadily within the standardisation measure. The quality management organisation has become part of the whole authority: each department and the roof organisation itself have inaugurated one representative assigned to keep the quality management system working and strive for improvements.

2) Quality management within contractors organisations

The ISO standards provide a framework for a contractor to establish a quality system. As ISO 9000 only establishes the baseline requirements, the standards are flexible enough to allow the development of an organisation structure reflecting the unique needs of an enterprise.

In addition to developing and implementing a quality policy that conforms to the standards, some contractors are also registering their quality systems. To enhance their ability objectively to judge a contractor’s quality control efforts, some owners now require an external registration and approval of the contractor’s quality system for awarding a contract.

The road owners may also find that a contractor’s documented application of the ISO 9000 standards simplifies their quality assurance efforts throughout performance and provides reliable means of managing an important source of project risk.

Therefore more and more contractors are establishing a quality system compliant with the internationally recognized parameters outlined in the ISO 9000. Doing so, the organizations will improve the quality of their services or products, and provide assurance to their customers that their quality system satisfies the fundamental precepts of quality management.

The principal instruments of ISO 9000 are the assignment of a representative for quality management with direct link to the board of directors in the company [5].

III. MACHINE TECHNIQUE

A. Demand statement

The use of statistics is essential in interpreting the results of testing on a small sample. Without adequate interpretation, small sample testing results can be quite misleading. When taking sample cores of several pieces, one might not find any defective pieces or might have all sample pieces defective although the construction measure was conducted properly and most of the plane is properly built-in and compacted.

[2] One has to mention that in Germany the authorities are organized within the state governments, even if administering roads that are financed by the federal government.

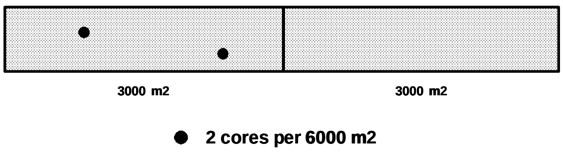

Fig. 2. Typical quality assessment of today providing documentation on less than 1/1000 per cent of a paved surface.

Due to the random nature of the sample selection process, testing results can vary substantially and their correlation to the produced quality of construction is doubtful.

Taking the example of road construction, the present quality assessment comprises that cores are drilled from the paved and compacted surface. For example, the requirement of the Swedish National Road Authorities states that for every 6000 m^2 (divided into two 3000 m^2 surfaces) two cores shall be taken randomly from one of the areas, as seen in figure 2.

If these cores meet the requirements both surfaces are approved. If not two more cores have to be drilled from the other surface. As indicated these test are spot tests more or less based on single values. It should be noted that these two cores correspond to 0.00026% or 0.00059% of the total surface depending on the diameter of the cores, i.e. ∅ 100mm or ∅150mm. It is questionable if these cores represent the actual quality of the surface. For instance, no information of the distribution, homogeneity is available. The tests do not either give any direct relation to damage. The quality documentation is cumbersome and moreover not available in digital form. Another important issue is that the results from these tests are only available after the production phase. It is obvious that the test results cannot be used to direct the production. It is also more difficult to use these values for knowledge transfer, as they don't necessarily correspond to the work performed and the achieved quality. The traditional quality assurance does not really encourage overall quality improvements. It is therefore desirable to use more suitable methods to check and evaluate the quality of performed work. This demand is answered by the below mentioned technology including machine data, process data and referring them to the position. This provides a continuous control of the paving and compaction effort.

B. General Considerations

Contractors usually have a fleet of machines from a number of manufacturers. These machines are moved to and from construction sites as they are needed on a day-to-day basis. Process data, which is collected on each machine, is transferred to the manager's office for evaluation each day or after finishing a task. The project manager is responsible for the analysis and storage of all collected data in order to assure a high work quality (see figure 3).

Machine manufacturers usually provide software for data evaluation, which allows the manager to analyze the provided data. Data, which is collected on the same type of machine, can only be combined if the machines are made by the same manufacturer.

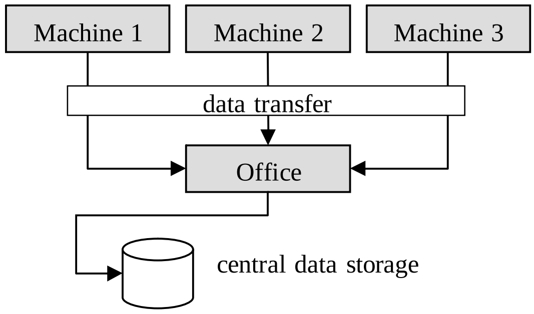

Fig. 3. Data acquisition and transfer of a construction project

There is currently no compatibility or portability between different manufacturers, an easy to use export of the data in a standardized way does not exist. The data itself is usually stored in a proprietary format that usually cannot be converted or exported to other systems.

To establish a total project management system in construction, provided process data has to be analyzed with one single software tool. This can be reached either by the ability to read all proprietary data formats or by providing an open data exchange format by the manufacturers. Such open data exchange formats exist already in several areas of construction.

Furthermore, all machines have to be equipped with sensor technology that allows an analysis of the achieved work, i.e. the available sensors have to provide project relevant data.

C. State of the Art

1) Machine information

Currently most manufacturers of construction machinery provide digitally acquired information about the engine and hydraulics system. The owner can review the status of electronic engine conditions like pressures, temperatures, and speeds as well as information like engine load factor, fuel economy, desired engine speed, estimated fuel rate, vehicle speed limit. Lifetime information for fuel economy, distance, average speed, fuel consumption, engine hours, and more are provided in most modern machines.

2) Process data

Process data, which allows the judging of the achieved work, is only available in a small number of machines or by add-on systems. The amount of sensors for process data acquisition is highly dependant on the field of construction. If the processes are automated like in shield tunnelling or rail and road construction, the degree of equipment is higher and the provided process data is more comprehensive. In other areas (e.g. building construction), hardly any process data can be collected as the work is performed manually.

3) Position

The position of the machine is a fundamental process information, which is provided by several add-on systems. Most of them are GPS[3] (+ RTK[4])-or laser-based systems that provide an absolute or relative position. The provided precision depends on the application. In general, these systems can be easily adapted to many kinds of machines.

IV. Requirements

A. Data acquisition and management

In all parts of the construction process, project data is generated and, in order to provide a total project management, has to be stored in one central database. The largest amount of process data is generated during the construction process which is supported by construction machinery. This machinery can be used to collect relevant data.

The amount of machine involvement depends on the type of the construction project (see Table I). The more machinery is used in a project, the higher is the amount of ascertainable data.

Data provided by machines can be distinguished between

- machine data,
- process data and
- analysis data.

Machine data represents the machine state and allows the analysis of failures and the performance of each machine (e.g. engine speed). Usually this type of data is available on many types of construction machinery as it improves the service in case of a breakdown. However the data often is not publicly available.

Process data consists of all data that is acquired on a machine about the construction process (e.g. position). It allows the determination of the place and manner a task was performed and the kind and amount of materials involved. Generally not all data is available.

Data that is calculated from process data already on the machine can be called *analysis data*.

TABLE I
TYPICAL INVOLVEMENT OF MACHINERY IN DIFFERENT TYPES OF CONSTRUCTION PROJECTS

Project Type	Involvement [a]
Earth works	+ +
Excavation pit construction	+
Road construction: Milling and recycling	+ +
Road construction: Asphalt or concrete laying	+ +
Railway construction	+
Railway overhauling	+ +
Building construction	-
Bridge construction	-
Bridge overhauling	- -
Microtunneling	+ +
Tunneling (shield tunneling)	+ +
Tunneling (conventional)	-

[a] The involvement ranges from "very little" (- -) to "very high" (+ +)

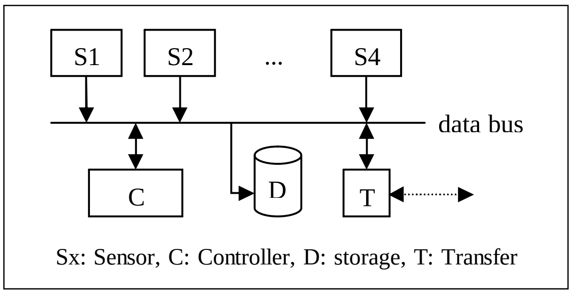

Fig. 4. Typical network on construction machinery

Usually this data is presented to the machine operator during the construction work (e.g. compaction value in earthworks).

Machine data and process data is acquired by sensors. Analysis data is computed by controllers or by advanced sensors. All components are connected with each other via a digital data bus. A data logger stores all available data for later retrieval and analysis. An optional data transfer between office and machine or between several machines can be done via a radio link.

Both the data storage and transfer are usually not available on construction machinery today. At least the data storage is highly necessary for the later evaluation of the performed work. The transfer of the contents of the data storage to the office can either be performed via transfer on a storage medium (e.g. solid state disk) or via a radio link.

B. Sensors and Controllers

The following information must be provided by a machine to enable project analysis and management:

- machine data, e.g.:
    - id/type of machine
    - tool size, capacity or similar
- process data, e.g.:
    - current time
    - relative or absolute position of the tool/machine
    - machine state (working, idle, ...)
- project data, e.g.:
    - machine cost (fuel, engine hours)
    - amount of material uses/built

Any additional information does greatly improve the quality assessment in the project management and depends on the machine type.

The presence of a controller that manages the data on a machine is not mandatory as long as all mentioned data is available. For advanced applications, a controller based system is necessary in order to provide the process data.

1) machine id or machine type

A machine has to identify itself and all recorded data has to be 'signed' by the machine to ensure that the data evaluation in the office can connect the provided data with the right machine. Also the type and size of the tool have to be provided by the machine.

2) Time

Generally the work on construction sites is performed by more than one machine at the same time. Therefore the time provided on the machine is important for the analysis, as the performed work of each machine has to be connected to the work done by all other machines. The time data on all machines must be synchronized to ensure a proper data processing.

3) Position

The position of a tool is a primary piece of information for evaluation. It is important to distinguish between the position of the machine and of the used tool (e.g. the screed on an asphalt paver, the hook of a crane). As all process data is generated by the work of the tool, the position of the machine itself (the chassis) is not of interest and the position of the tool has to be provided (see figure 5).

Usually, the point of work should be made available, or, if the tool has a working line or area, the centre point of the tool should be provided along with some information about its geometry.

On machines that have more than one tool (e.g. two-drum compactor), the position has to be defined in advance. On all machines, each position must be assigned to a timestamp and each piece of data must be assigned to a position or a time in order to be able to assign all data to time and place.

4) Machine state

A machine has to store each change of working state and has at least to distinguish between the states working, idle and transport. The latter state means the moving of the machine from one place to another without performing any work (e.g. asphalt compactor refilling water).

5) Project data

A machine can also provide information, that can directly be used for project and quality management, e.g. machine cost (e.g. calculated from machine hours, fuel consumption) or the used material.

C. Data Precision

All measurements have to be taken with an accuracy that is high enough to allow a quality control of the performed work. The minimum accuracy required is one tenth of the precision that a work has to be done with (e.g. if the required evenness in road construction is ~1 mm per meter, the accuracy of the evenness measurement has to be 0.1 mm).

D. Data Handling and Processing

At the same time, the data has to be stored on the machine in a fast and efficient way. The stored information is used for analysis after its transfer to a standard computer.

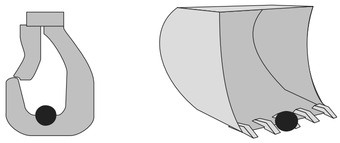

Fig. 5. Example points for the position information of a tool

1) Software Interface

Process data is collected during the whole work day and can accumulate to a large amount of information that has to be stored in a fast and efficient way. Usually, not all data available on a machine has to be stored, so a filter mechanism is applied to the data input. Data storage has to be fast due to possibly short reception intervals of process data. Storing the data in a binary format is fast and compact and has to be preferred.

To be able to use the data in the office, it has to be converted to a format that can easily be imported to standard office software for analysis like the XML format. XML is platform independent and flexible enough to provide the possibility for custom extensions.

2) Hardware Interface

Also the hardware interface has to be compatible both with the machine hardware as well as standard computer hardware. The data storage on the machine will usually be connected directly with the machine field bus (e.g. CAN-Logger at a CAN-bus). The data is filtered and stored on a medium that can be removed from the machine and plugged into standard computer equipment (e.g. USB or Compact Flash). If a data transfer via a radio link is used, the transmission format has to be compatible as well (e.g. RS232 or WLAN).

V. EXAMPLE SYSTEM FOR ROAD CONSTRUCTION

With the mentioned objectives for a continuous quality control in mind, a consortium comprising five partners with complementary skills was established in 2000 to develop products for road construction. This development project called OSYRIS (Open System for Road Information Support) was conducted by five partners: LCPC – France, Moba – Germany, University of Karlsruhe (Technology and Management in Construction) - Germany, Tekla Corp. – Finland, Skanska – Sweden, with support of the European Union Program “Growth”.

At the end of the initial development project in January 2003 several products and pre-normative data exchange formats were released by the consortium. The complementary and mutually compatible products developed by OSYRIS – consortium respond to the requirements of the European road construction industry. These products effectively support the gathering, processing and management of data during the design and construction process, resulting both in more economical construction methods as well as qualitative improvements to the road itself.

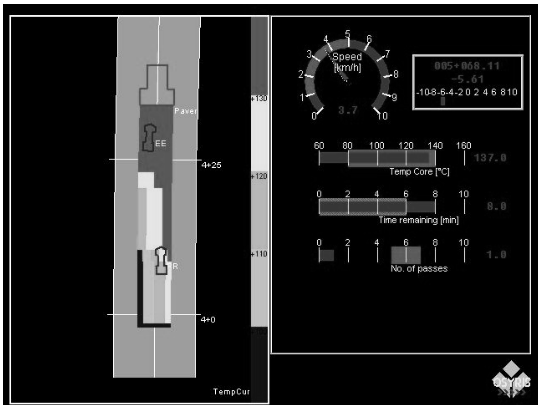

Fig. 6. GUI for the driver of the Compactor, including remaining time for conducting the compaction work

This support continues throughout the entire life cycle of the road, beginning with the design phase through optimization of the construction process to repair and rehabilitation measures on existing roads.

OSYRIS components may be installed and operated on-machine, for example on a paver or a compactor, or run off machine, for example in an engineering department. A third product group provides the link between the two mentioned previous and establishes the IT-framework for both on and off the construction site (www.osyris.org). The complete system and its components were presented during ISARC 2001 in Krakow [1].

The authors were and are involved in particular in the development and maturing of the products on-machine and the IT-framework and contribute to the standardization of data exchange between the different components and actors.

The focus of these technologies is the improvement of the work executed by means of on-line control of key performance parameters for the paving and compaction operations. E.g. a new technology for controlling the paver tool, for the first time the thickness of the spread asphalt layer is controlled; secondly the positioning information from levelling can directly be used for the documentation of the constructed surface.

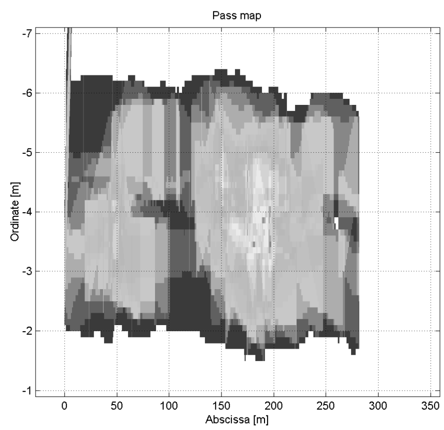

Fig. 7. Pass map for foreman and quality documentation to the owner

So far this had only be possible with costly post-surveying; a solution for low-cost positioning of rollers; a Compaction Assistant containing an Asphalt Temperature Estimation System, ATES providing the information for the drivers of asphalt compactors, how much time is left to perform their compaction job before the asphalt is too cold to be compacted. System components were extensively tested during worksite trials and have been undergoing further maturing since then. Some of the functionality is shown in the following diagrams, revealing the continuous information flow and data gathering from design to paving and compaction and data post processing. Two of the various opportunities of information handling for the different actors involved in the compaction work are demonstrated

Recently OSYRIS-technology exploited to a new machine type, demonstrating the adaptability of the products to other target machines playing an increasing role in the life cycle of a road: A first milling machine of Wirtgen, equipped with Moba-technology following the OSYRIS-paradigms, was delivered upon order to the former member of the consortium Skanska.

VI. Conclusions and Outlook

So far there does not exist any fully integrated solution for Total Quality Management in Construction. Remarkable systems are available for a small number of applications which are highly mechanised and with broad use of machines. The authors expect a huge increase of available systems within the next decade, provided that the manufacturers of construction machinery agree on common standards for data exchange.

The other actors involved (contractors and authorities) will contribute to such a broader use by demanding technology that can interface with their own quality management systems.

The use of such technology will generate a higher profit for all parties involved and the tangible result of longer lasting roads.

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