DIGITAL ALLOCATION OF PRODUCTION FACTORS IN EARTH WORK CONSTRUCTION

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ABSTRACT

Currently, the development of information technologies for construction processes in earth work is focused on sensor systems, machine control, and building information modeling (BIM). These systems have been developed independently and it seems beneficial to link and combine the information available in these single systems to enable a global optimization of the production processes.

An integrated system collects and stores data from sensor-equipped construction machines to connect them with information from the planning phase, thereby leading to a higher level of transparency. This transparency can be used to identify bottlenecks and unproductive working times such as waiting periods. The system can provide assistance for the construction manager to detect reasons for these kinds of distractions. Hereby a continuous improvement process is induced.

This paper will introduce the described system above and show the benefits of the merged use of current developments in information technologies. Moreover, it represents the ongoing development of a system prototype.

KEYWORDS

continuous improvement, visual management, earth work, resource allocation, virtual reality, information transparency, control center

ANALYSIS OF EARTH WORK PRODUCTION

From a systematic point of view, a production system consists of different elements that interact according to a certain organization in order to transform a given input into a - from the costumers point of view - desired output. A production system consists of multiple smaller subsystems, which interact in order to reach the desired output[4]. While the production system is working, different time- and place-dependent influences affect the production system. Figure 1 shows an interpretation of the common understanding of a production system. (Arnold and Furmans 2009, Gutenberg 1970, Günther and Tempelmeier 2009, REFA 1984)

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4 This classic transformation view (compare (Koskela 2000)) could be applied to arbitrary hierarchy levels of a system.

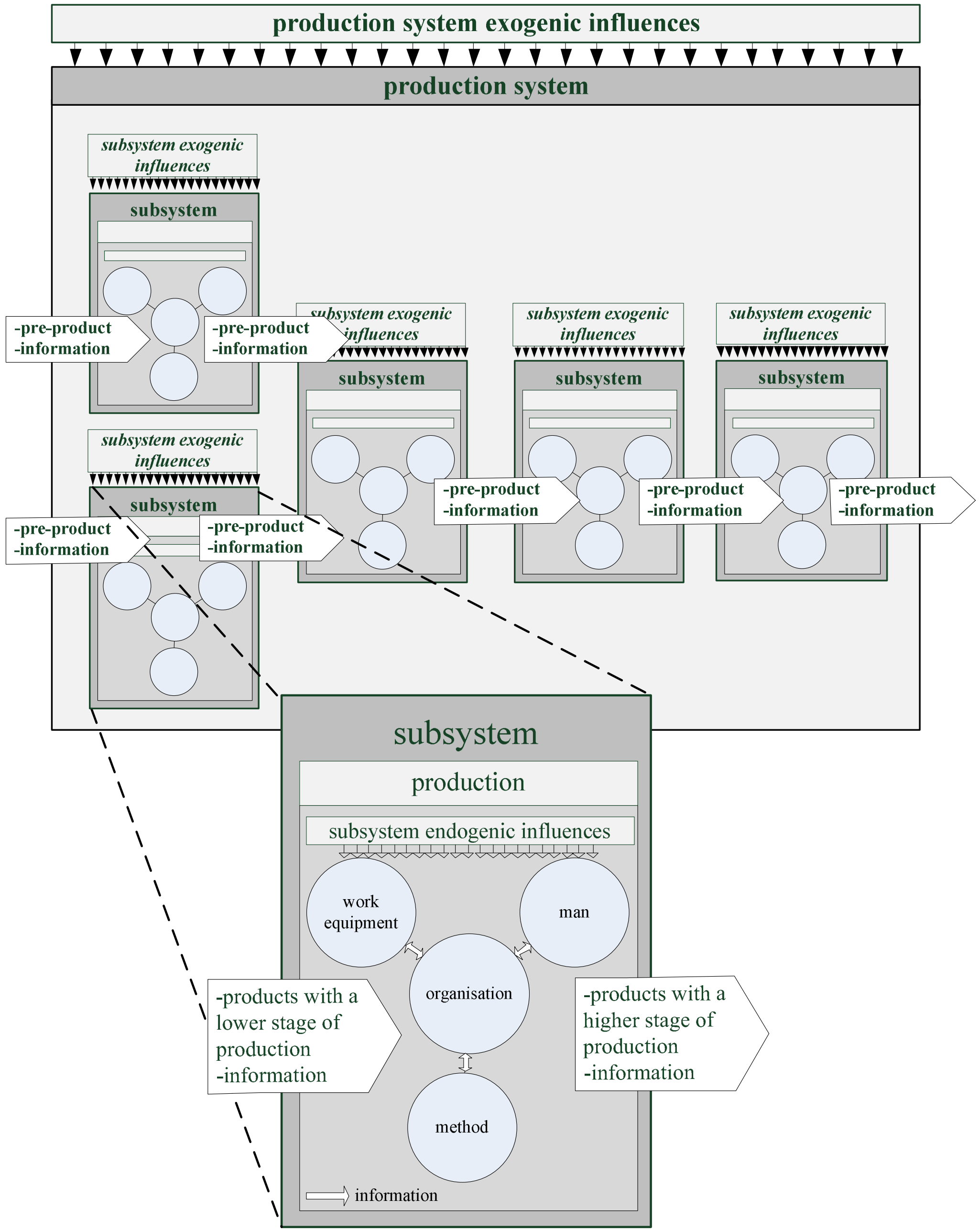

Figure 1: production system

The predominance of the transformation view is obvious. Despite this predominance, the figure adumbrates also the meaning of flow. Nevertheless the obvious remaining problems are the interfaces between the systems.

There are extrinsic influences that affect the production system (production system exogenic influences) like e.g., ecologic, political and social influences as well as intrinsic influences (subsystem exogenic and subsystem endogenic influences). Subsystem exogenic - but production system endogenic - influences result from the interactions between the subsystems e.g., waiting time for products. Subsystem endogenic influences evolve from the combination of the production factors (man, work equipment, products, information, and organization). Obviously, the exogenic influences of the subsystem emerge from endogenic influences of other subsystems and the organization of the production system itself. The influences are as mentioned above time- and place-dependent. The variability of the influences cause variations in performance and thereby generates problems on the subsystem interfaces.

According to Koskela (2000) there are different options to eliminate or minimize the impact of variability. These are buffering of flows, accepting lower utilization levels of resources (which equates to acquisition of extra capacity) and accepting lost throughput. Furthermore, Koskela (2000) shows that the possible solutions in case of variability are:

- A production system design with low inherent variability
- A controlling system that avoids the cascade or point-wise deviation of variability to other tasks and minimize the unnecessary penalties for variability
- Continuous improvement (locate sources of variability and try to minimize the impact)

The second and third option are the main focus of this paper, and within them the improvement of the information flow. A better information flow is required to achieve a better management of the construction site (Kiziltas et. al. 2009, Howell and Ballard 1997, Womack and Jones 2003). The above mentioned explanations lead to the following hypotheses:

1. The longer the cycle time of information flow is, the more likely becomes a divergence between planning (which implies forecast) and reality.
2. Due to the high inherent variability in earthwork processes, short cycle time of information exchange is needed to reach the necessary transparency for management.

PRODUCTION PLANNING AND CONTROLLING IN EARTH WORK

Like any other production, the first step of construction production in earth work is the planning phase. In this phase, the target parameters like costs, deadlines and quality are set and appropriate production factors are selected. During the definition of these targets, forecasting of the relevant factors of influence is necessary. Therefore, the planners anticipate the future influences. The longer the forecast horizon, the more likely becomes a divergence between the forecast and reality. This hypothesis is validated through different interviews with construction managers, public clients and project managers. Furthermore it can easily be explained as follows: A long forecast horizon implies the estimation of all possible project influences. This means the identification of all parameters as well as the knowledge of the overall impact - which can be dynamic - of the different parameters. Due to this fact it is very unlikely that long-term planning and reality correspond to one another. This implies that controlling and subsequent adjustments are necessary (see Figure 2).

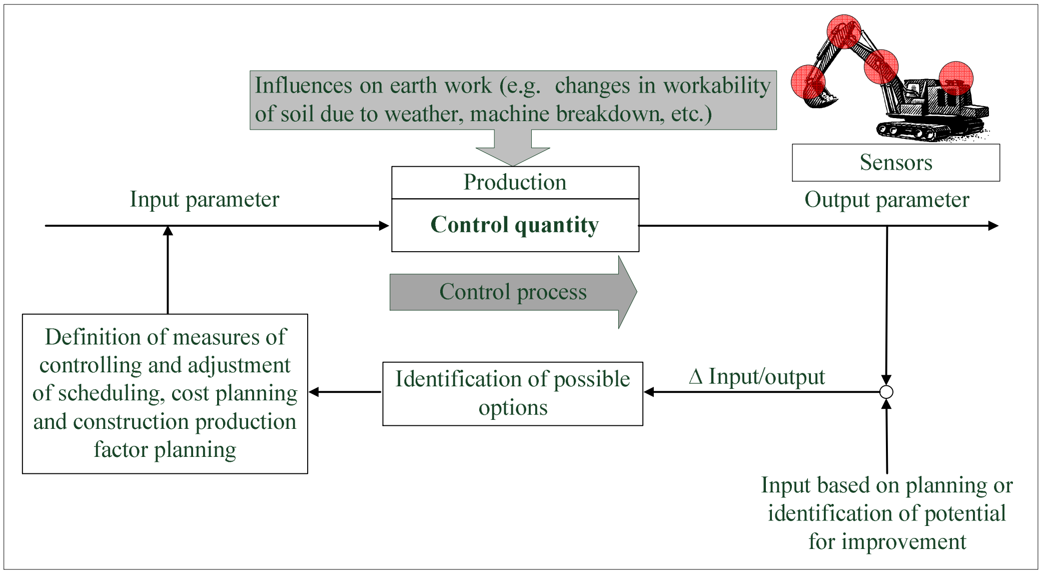

Figure 2: control cycle

The realisation of construction projects in terms of agreed costs, time and quality targets are the daily business of the construction industry. Given the dynamics of construction projects, it is necessary to identify appropriate controlling mechanisms.

Particularly in earth work, process information is needed in short time intervals due to the continuous progress of the construction and the existing dynamic conditions (e. g. soil properties and climatic influences). The adjustment of the production network - and sometimes even of the production method - is necessary if boundary conditions change. Furthermore, process information is required to identify potential for improvement and to initiate the corresponding actions of controlling. The collection of process data is bound to the existence of a suitable - simple handling and integration - system. In contrast to the stationary industry, these kinds of systems do not yet exist in earth work.

A more transparent, resource efficient and flexible production is needed in order to increase quality and productivity, especially in earth work. High degrees of machine efficiency and traceability are required. Waiting- and down-times have to be reduced. The involved operators need appropriate decision support and suitable representation of information which can be supported by appropriate IT-solutions. The optimization of information logistics in earth work offers a high potential.

Formoso and Isatto (2009) identified several reasons for the ineffectiveness of production planning and control in construction, including:

- The little effort that is spend in gathering reliable data and to the dissemination of information (Laufer and Tucker 1987)
- Exchange of information that is usually focused on short-term decisions and has no link to long-term plans (Formoso 1991)
- Uncertainty as one of the main sources of problems, whereas little is done to minimize it (Cohenca et al. 1989)
- Construction managers making decisions based on their intuition and common sense, rather than on data systematically collected and analyzed (Lantelme and Formoso 2000)

Data gathering seems to be difficult and unsatisfactory in construction. The exchange of information is based on the transformation view and thereby focused on details rather than the holistic view. Uncertainty cannot be managed without identifying the underlying reasons and thus data gathering is required. Without data of the production processes, the construction manager makes decisions based on intuition and common sense. As a result, better information logistic is needed.

A better information logistic and thereby a better transparency could be reached through better generation of raw process data, improved data preparation and representation of information - based on the generated raw data - or shortening and fastening information flow.

Increased transparency can lead to an improved project performance. This can be explained due to the decrease of missed possibilities for process improvement e.g., the reallocation of production factors. Due to the specific project environment (weather, soil conditions, changing local work conditions etc.) earthwork processes need appropriate real-time process data which is presented through a suitable interface. As a conclusion processes variability leads to an increased requirement of process information. Therefore, both hypotheses can be preliminary considered as validated.

This conclusion is supported by the mentioned interviews and an extensive literature analysis. Furthermore, many current developments in research and industry concerning earthwork try to improve the information flow, which implies a real need.

In the next section a new concept of information flow is introduced and the ongoing development of a prototype discussed.

CONTROL CENTER

The technical foundation and requirement for this system is to equip the building vehicles with integrated sensors of two kinds; GPS-sensors with increased accuracy (supported by tachymeter and laser scanning) and additional sensors to collect e.g., the exact position and orientation of the excavator bucket or the dozer blade. Also technical data like maintenance interval, amount of diesel or engine oil pressure are known so that a vast data basis exists.

Thus, to realize a short-term feedback of vehicle performance data, an improved and expanded data flow from and to machines is required. All recorded data shall be saved and distributed by a consistent communication platform. It is used directly on the construction site, stores position and orientation of building vehicles among other things in a database and allows its real-time demand and distribution. There is also a need for the development of a dynamic building model for earth work, a standardized description of geometry/terrain, which shall be combined with a construction process model to gain a holistic 6D-model (geometric data, schedule, costs and quality) of the construction site.

INFORMATION TRANSPARENCY

The basic idea is to use transparency to reduce waste (Koskela 2000, Tezel et al. 2010). The area of earth work is connected with significant uncertainty and characterized by a high degree of dynamics. Nevertheless, the principals of transparency are still applicable for a continuous process improvement. In order to implement these principals a new instrument has been created: A control center that combines all the information and offers more transparency to all the involved parties. By using this control center, information from the actual situation can be combined with those from the planning phase, leading to a higher level of transparency. This construction site control center may make a dedicated contribution to the area of “Visual Management” (Tezel et al. 2009).

Via a construction wide communication platform the control center gathers all the information of the sensors-equipped building vehicles processes and presents them by virtual reality (VR). Virtual reality is an interactive type of human computer interface and provides opportunities of an ergonomic and intuitively visualization of these information (Biocca and Levy 1995, Sherman and Craig 2003).

Planning and monitoring a construction site is not only a spatial complex problem but also strongly multidisciplinary shaped. Many people from several different disciplines and educational backgrounds and with different amounts of information have to work together. VR (and also Augmented Reality, see next section) is able to make a significant contribution to achieve this. By using VR visualization techniques an ergonomic and intuitive layout is possible, which professionally supports all types of users.

This control center makes it possible to find the deviations between planning and execution phase at shorter intervals, therefore providing a basis for consequent analysis of these deviations and allowing to identify the root causes by e.g., the 5-Whys-Method (Ohno 1988). This enables an implementation of a continuous improvement process.

Based on a visualization of the differences between the planning and executional phase (respectively comparing actual versus target performance), an improvement of the construction site at two different areas is possible:

1. Changes through the dynamic of the construction process (change of the soil class, weather conditions, etc.) can be discovered and a faster response is possible by using a decision support system.
2. Improved constructive cooperation and coordination (e.g., reduced waiting or unproductive times) ensures that potentials will be exploited and a value maximization achieved.

The sensor-equipped building machines send their data to the control center, where combined with the planning and BIM data a holistic construction model is created. This model will be visualized by virtual reality. A human-computer interface allows the site manager to interact with the system. Linked with information of the planning phase an automated variance comparison can be performed by the control center. An easy-to-follow traffic light system represents the situation at the construction site in real-time and furthermore it is able to alert the site manager in case of a critical threshold value exceed. Thereby it fosters the construction manager and helps him managing the flood of information by filter-mechanism. In order to understand more precisely what happens in such unclear alert-situation context-sensitive information can be called and retaliatory actions taken. A graphical overview of the control center’s architecture can be found in Figure 3.

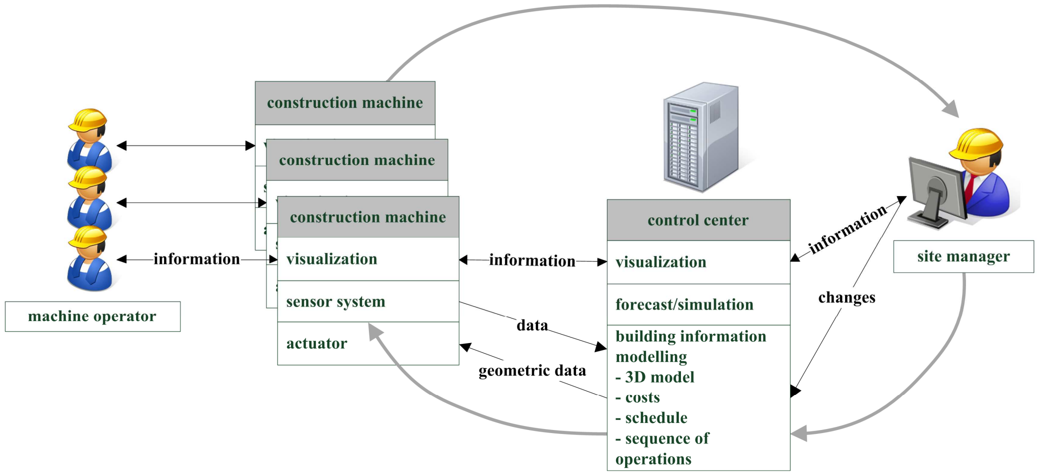

Figure 3: control center architecture

Referring to the current situation on the construction site, comparing performance data of construction machine teams, time schedule and costs of the construction system, the control center is able to make a proposal for a new allocation of the building vehicles. The site manager is able to confirm this suggestion, enter some changes or, based on his experience and greater knowledge; assign the implementation of another possible solution.

Moreover tasks with an added 3D-target-terrain-model can be sent to the building machines, where it can be used for a 3D machine control of the actuators. For example, the shield of a dozer can be automatically adjusted in height to build the target terrain as accurate as possible. Also the collected sensor data allows an automatic generation of the updated digital terrain model. Furthermore, the task-information is displayed to the machine operator, so he is well informed about his task. He is also able to request further information or open a communication channel to speak directly to the staff.

In addition the control center offers a simulation module. Based on the actual performance data of the machines it allows forecast in shorter intervals and is therefore showing more precisely how current tasks compare against the plan. During the planning phase this component can also be used to gain a well adapted initial plan. Using average performance data instead of the actual one and a 3D model of the construction site for instance the optimal amount of dumpers according to an excavator can be identified by simulation.

The use of this control center leads to a transparent working environment with disciplining effects. In addition, discrepancies between planning and execution phase (e.g., changed type of soil) are documented. This might be the base for a fair change-order-management in case external influences unexpectedly cause delay. The quality of the earth work is proved by the visualization of the automatically generated digital terrain model - the actual produced terrain - compared to the target-geometry.

The control center information does not only show the direct environment but also vehicles working far away, which allows not just a local but a global optimization. Consequences of changes in the sequence of operations are automatically adjusting the time schedule. The impact will be shown directly. The same applies to the interaction of costs, so the site manager is knowledgeable at his best. In this manner an overview of the entire site can be taken and a direct management is possible.

ON-SITE USE CASE AND PROTOTYPE

The augmented reality (AR) technology can be used to support the construction manager. AR expands the real-world with virtual, context-sensitive information (Azuma 1997, Milgram et al. 1994). Bowden et al. (2006) and Dunston and Shin (2008) also see AR as the adequate technique to optimize processes at construction sites and recommend the use of mobile devices.

In detail, the construction manager is able to access context-sensitive information via his mobile device in dependence to his actual position and view (through a camera on his devices, compare also (Behzadan and Kamat 2007)). By overlaying a digital terrain model, variance comparison is possible. It is easier, even for experienced workers, to recognize 3D models instead of mentally abstracting 2D drawings of a complex building project (Issa et al. 2003). Also occlusions from virtual objects by real ones are realizable (Behzadan and Kamat 2010). At a site inspection the construction manager can be supported by faster information on a reliable database.

Visual tools can easily create an "easy to see and understand" work environment even for untrained and inexperienced workers (Tezel et al. 2010). With use of mobile devices and improved and faster information a pull principle of building vehicles can be implemented. Based on the dynamics in earth works, variability in capacity utilization are the norm rather than the exception. The mobile devices provide a high adaptation potential to this situation as they can be used for specific information forwarding. Consequently this increases flexibility as the building machine operators are able to provide regular feedback reports and ordering (pull principle) e.g., new material (in case of a dozer) or another dumper (in case of an excavator).

On the base of a requirement analysis, performed by interviews of experts and future users, a prototype has been developed. Among other things it was requested which objects, resources and parameters are important and relevant and should be visualized in which context. At the same time it has been questioned which interaction, if at all, with the visualized data should be reasonably conducted. Additionally necessary action and animations, like alarms, were identified. Based on these interviews, a human-computer interface has been implemented that fulfills the requirements and is tailored to the needs of the users. (Kirchbach and Runde 2011)

For test purposes exemplary a virtual construction site has been drafted and, in order to achieve a more realistic test environment, a construction site mock-up ("in-house sandbox") was built. First tests at the virtual construction site as well as at the site mock-up have been carried out. The experience made in these tests underlines, that using the way of retrieval of information by the control center and mobile devices through VR and AR has been very sufficient.

Further tests and presentations in front of future users will be performed and the prototype based on test results revised. A final test on a "real" construction site is in the planning phase.

CONCLUSION AND FUTURE WORK

Despite of an increasing access to information, the use of information is still unsatisfactory due to the effort in indentifying and combining the applicable information. Furthermore, the different sources of information are in most cases not compatible. However, combined information is required to allocate the production factors. A direct integration and processing of these data provides an enormous potential for improvement. Especially in earth work, the locally gathered raw data on construction vehicles can be used for active controlling and continuous improvement.

In this paper it could be shown, that a better information flow in earth work is necessary. A better information flow can lead to an increased transparency and therefore enabling the identification of possibilities for process improvement. The identification of improvement potentials leads to an induction of continuous improvement. Furthermore the paper presents the current developments of an ongoing research project. A prototype has been developed and is currently being tested. The results are very promising and the used information technology enables the production processes to be made more transparent for construction workers. Information transparency is a great opportunity to an enhanced performance even in the highly dynamic area of earth work and promises great benefits.

Further work is required to define in detail the reasons that cause the variability in earthwork construction processes as well as their scale and impact on the overall production process. Especially the quantification of the above mentioned relations is necessary.

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