DIGITAL KANBAN FOR EARTHWORK SITE MANAGEMENT

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ABSTRACT

In the manufacturing industry the use of information systems based on modern communication techniques, such as Material Requirements Planning (MRP), Enterprise Resource Planning (ERP) or Customer Relationship Management (CRM) Systems, is standard and has long been deployed with success. But these systems depend on consistency in the production systems, which a construction site is unlikely to offer. Furthermore the construction process is highly fragmented and in comparison to the stationary industry very complex. Due to the dynamics of the processes on earthwork construction sites, new flexible logistic concepts are needed.

This paper will present “digital Kanban”; a method to dynamically allocate the best possible match of excavators and transport vehicles at earthwork construction sites. With regard to the principles of jidoka, “intelligence” is transferred to a control centre in order to detect abnormal conditions, enabling it to respond rapidly.

Excavators are pulling empty dumpers and dozers are pulling loaded dumpers. In case more than one excavator is requesting a dumper, the current performance of the excavators and their allocated dumpers at the present as well as the distance to be travelled will be analysed. The digital Kanban cards are created at the last responsible moment: If a dumper just unloaded or is fully loaded, it requests a Kanban card and only then the Kanban card will be generated.

To quantify the optimization potential, results of stochastic simulations based on the Monte-Carlo method will be introduced.

KEYWORDS

Kanban, IT in Lean, production control, visual management, Lean Construction

INTRODUCTION

When comparing the construction industry to the manufacturing industry, it can be established, that construction has to catch up. The normative costs per unit in other sectors are falling, the costs in the construction industry are rising (Paulson 1995). Also the use of information systems, such as Material Requirements Planning (MRP), Enterprise Resource Planning (ERP) or Customer Relationship Management (CRM) Systems is standard within the stationary industry and long been deployed with

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success (Brynjolfsson and Hitt 2003). Their transfer to construction seems promising, but these systems depend on consistency in the production systems, which a construction site is unlikely to offer as the construction process is highly fragmented, and in comparison very complex (Akinsola et al. 2000, Shi and Halpin 2003). Especially the area of earthworks is connected with significant uncertainty and characterized by a high degree of dynamics not only due to complex processes but also to the specific project environment (weather, soil conditions, changing local work conditions etc.). (Gransberg 1996, Kirchbach et al. 2012, Schexnayder et al. 1999)

A constant monitoring of the processes hardly exists in earthworks (Navon et al. 2004, Ligier et al. 2001). Stand-alone solutions for certain applications are available, these however focus only on part of the construction tasks. Data interfaces between these applications are missing, although it is necessary for the tasks of a construction site. The existing "islands of automation" by Hannus (1996) have to be combined from different developments to one solution. Previously this was not the case, leading to several departments using their own software each and therefore to an increased workload and less efficient processes (Dave et al. 2010).

The need of new types of logistic concepts in dynamic environments is recognised (Leukel et al. 2011, Liu et al. 2007). This leads to the idea of supporting lean principles with information technology: This paper will present "digital Kanban"; a method to dynamically allocate the best possible match of excavators and transport vehicles at earthwork construction sites in order to optimize the productivity of the whole construction site.

The chosen research method of this paper is design science research (Vaishnavi and Kuechler 2007), which is an approach to "develop scientifically grounded solutions that are able to solve real-world problems" (da Rocha et al. 2012). In alignment with design science research guidelines (Kuechler and Vaishnavi 2008), visits to construction sites preceded this research. The conducted informal conversations and discussions led to the conclusion, that due to missing data, the control of the process sequences can only occur insufficiently or rather temporally delayed and therefore reactively. Especially during the allocation of transport vehicles to excavators, waiting times often occur. The current situation is opaque and not clearly graspable. Furthermore problems are usually solved locally and connections or rather effects on other processes at remote locations are hardly or not at all considered. The gained knowledge is confirmed by the following literature review.

EARTHWORK PROCESSES

Earthwork processes on construction sites are very significant in terms of cost and productivity (Navon et al. 2012). Figure shows the simplified process of an earthwork construction site. The material will be excavated and loaded onto a dumper. This dumper delivers the material to the point of placing, where it gets distributed with a bulldozer. The downstream process of compacting the material with a roller is excluded in this paper.

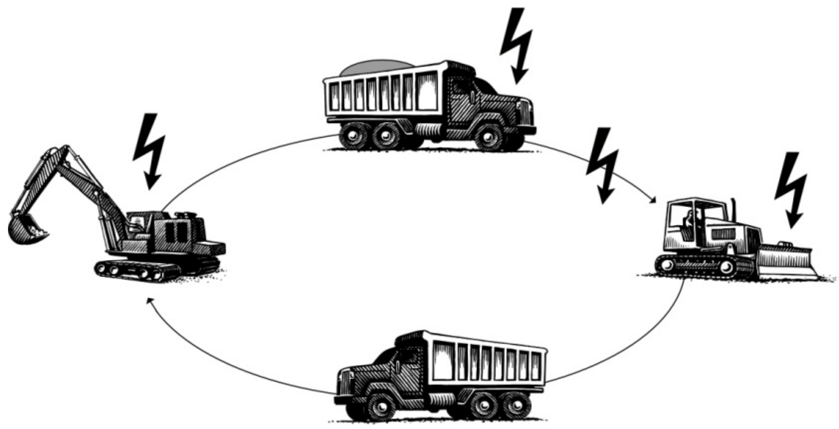

Figure 1: External influences on earthwork processes

The earthwork processes are influenced by many different factors. The performance of an excavator can be affected through changing or deviating (from prior information) soil conditions. Machine-related restrictions or failures can occur or the performance impaired by human factors - an inexperienced machine operator for instance. The same applies to dumpers and dozers. Weather influences in terms of temperature, precipitation and also wind play an important role, as they can lead to a disturbance of the processes and to complete restrictions on the site roads or a considerable slow down.

A change in performance or a failure can cause a disturbance in the flow of the whole process. Instead of dumpers driving evenly distributed at the construction site, crowding of dumpers may occur. As a consequence excavators are sometimes not able to load a dumper and sometimes the dumpers have to wait until they can get loaded. Through restriction on the site roads, which only allow a certain capacity, more waiting periods originate. Primarily restrictions within the excavation are important, as this is not only the determining factor but also the most cost-intensive. Waiting and down times for excavator have to be prevented.

The change of a soil class for example may not be detected by the machine operator. Also is the impact to the whole construction hardly or not at all obvious to the machine operator. In this manner a creeping deterioration of the construction site performance can evolve. The longer a problem consists or remains undetected, the bigger is the potential damage (Navon 2005).

The disposition of the dumpers is set up statically. The dumpers are assigned to fixed production lines, which means they circulate between the same excavator and dozer. An adaption to current circumstances does not take place.

DATA COLLECTION ON CONSTRUCTION SITES

At construction sites not enough effort is spent in gathering reliable data and additionally this data is not widely distributed (Laufer and Tucker 1987, Ligier et al. 2001). This is confirmed by a survey by Navon et al. (2004): It says, that most of the asked construction companies do not use process control on construction sites. If process control takes places, a study by McCullouch (1997) shows that 30% to 50% of the time of the monitoring is spent with collection data as well as analysing it. Traditionally manual data collection is carried out, which is slow and inaccurate

(Davidson and Skibniewski 1995). (Navon et al. 2004) The most economic version of data collection is an automated one (Navon 2005). Even if sensor technology has developed noticeably within the last 20 years, it could not change the fact, that the current state of a construction site remains difficult to grasp (Saidi et al. 2003). The missing information and insufficient management of available data lead to an increase in cost and time (Navon 2005). The need for an automated data collection on construction sites is apparent in order to enable a real-time management (Sacks et al. 2003).

A look ahead, into the year 2020, by Froese et al. (2001) reveals that access to all information at all times will not only be necessary but also offered by IT tools. "As-built information" and "virtual progress monitoring" are required on construction sites (Bowden et al. 2006, Sarshar et al. 2002). The potential of information technology for civil engineering is acknowledged and its usage welcome, but adaptations to the needs of the construction industry are missing.

Bowden et al. (2006) determine, that the use of IT tools in construction is low, as these tools are not tailored to the needs of the construction industry. For example in the stationary industry the tasks reach to the worker, monitoring respectively the use of IT tools within this environment is easy. But in the area of construction things are different: The worker moves to his task and has to take his tools into a new environment frequently.

A survey by Barthorpe et al. (2004) indicates "that the construction industry can learn a great deal from the application of the ERP system used in the manufacturing and service industries". Construction firms are aware of ERP, but "very few organizations have so far implemented an internal system" (Ahmed et al. 2003). "No [ERP] system specifically designed for the construction industry is yet available" (Yang et al. 2007) and in order to enable these specific implementations, it is necessary to develop a "basic theory for [...] construction enterprise resource planning systems" (Shi and Halpin 2003). Chung et al. (2008), Chung et al. (2009) and Tatari et al. (2008) for example have developed approaches in this area. Despite the missing basic theory "major ERP vendors designed various construction industry specific solutions, but few if any have achieved widely acknowledged application success" (Tatari et al. 2008).

This is also reflected by the work of Tatari et al. (2007) who, based on a study of 101 construction companies in the USA about "Construction Enterprise Information Systems" (CEIS), showed, that only 16% of the participants are satisfied with their CEIS implementation. Additionally only 1.3% cover the whole supply chain with their system and only 12.7% the complete internal company processes. All other participants use their software solutions only for partial aspects. Aggravated by the fact, as described by Rettig (2007), that even if a change in processes and an ERP-implementation are strived, only a few companies achieve this objective and are able to benefit from its advantages. Again, it often leads instead of an integral solution however to the use of many, different software systems. Referring to Dave et al. (2010) it can be assumed, that the full potential of the use of information and communication technologies is not always recognised by the companies and from the view of the construction industry that the core issues of information and communication technologies are not designed for construction. Thus, a combination of information technologies and lean management principles can be helpful.

DIGITAL KANBAN

The basic idea is to set up a higher-level control centre, which allows the real-time monitoring of the construction site in order to detect abnormal conditions and therefore enables quick response. The technical foundation and requirement for this system is to equip the construction machines with integrated sensors of two kinds; GPS-sensors with increased accuracy (supported by tachymeter and laser scanning) and additional sensors to collect for example the exact position and orientation of the excavator bucket or the dozer blade. Also technical data like maintenance interval and the amount of diesel or engine oil pressure should be known so that a vast database exists. Combined in a multi-model container this data is ready to be forwarded via a construction site wide communication platform and saved in a construction site control centre. For more information see Kirchbach et al. (2012).

With the use of the presented control centre approach and the sensor technology the process of detecting an incident and reacting appropriately can be improved. As presented in Figure 2, the construction machines not only exchange information but also send their data to the control centre, allowing a global view of the construction site. This information flow, which does not exist at the moment, would enable a new way of process management at construction sites.

TRANSPARENCY

Within the control centre the construction manager receives a higher level of transparency regarding the current events at the construction, providing him with the possibility to take more reliable decisions: If there is an insufficient level of transparency, decision can only be based on conjecture and assumptions (Askew et al. 2002). It also means it is possible, that these assumptions could be wrong and therefore inappropriate decisions are made. If additional to the higher transparency connections and dependencies to other processes, can be shown, the construction manger is able to take more reliable and construction-site-global optimised decisions. The knowledge gained from this kind of system can be integrated in the daily as well as weekly planning to see how the construction site develops and the higher level of transparency will most likely reveal further optimization potential.

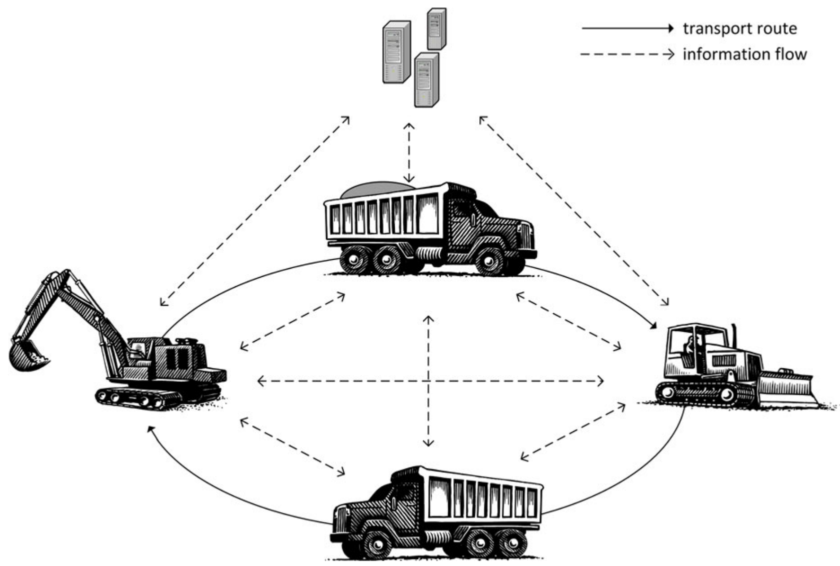

Figure 2: New information flow through sensors and information technology

The everyday work at a construction site can be made difficult by too high levels of automation, as construction is characterised by changing circumstances and depend on a high degree of flexibility. It is hardly possible to cover every imaginable challenge with rules within a software system. Therefore it is indispensable, that the construction manager can interfere manually, reject or pass suggestions of the system, add changes or based on his experience and knowledge create an own solution. So it is even more important, that the most flexible and intuitive component, the "construction manger", is provided with information at the best.

With regard to the principles of *jidoka*, "intelligence" is transferred to the control centre in order to detect abnormal conditions, enabling it to respond rapidly: The operating dumpers are available to the control centre as a assignable units. According to the current performance of an excavator, dumpers can be assigned beyond the so far fixed production lines to other excavators. This leads to the distribution being adapted to the excavators performance and minimizes the overall waiting times of the excavator. Thus empty dumpers can be pulled, based on a flexible Kanban system.

Considering that multiple excavators could request a dumper simultaneously, a strategy for this case has to be prepared. The simplest would be to follow a "first-come, first-served"-principle. In consideration of a global optimisation of the whole earthwork construction site, it is reasonable that the control centre undertakes a prioritisation of the Kanban cards.

KANBAN CARDS

The methodology is technologically realised by digital Kanban cards, on which the excavators not only provide their current performance but also when they are in need of a new dumper. In this case an estimation of the loading time of the current dumper, if present, is done and extrapolated at currently waiting dumpers or dumpers on their way to the excavator. The estimation of the loading and driving times takes place as a moving average on the current collected data of the previous loading cycles respectively driving speeds and times. Using a moving average also prevents unnecessary reallocation due to a short-term interruption or fluctuation in performance. At the same time the driver of the excavator has an instrument usable as an Andon chord in his cabin allowing him to report a threatened trip or generally an upcoming problem. Proactively this information can be taken into consideration within the further dumper disposition or, depending on the severity of the problem, the excavator can be removed from the processes for a certain amount of time to resolve the problem.

The Kanban cards are created at the last responsible moment: A dumper, which just unloaded, requests a Kanban card, the control centre analyses the current situation at the construction site and only then the Kanban card will be generated. In consideration of the dumpers' time of arrival at the excavator in relation to the time when the excavator needs a new dumper, the dumper receives a Kanban card. Thereby, a prioritization towards the expected performance happens, so that excavators, able to bring a higher performance, are preferred.

This criteria can also be the urgency of a task instead of the performance. If a (sub)task has to be finished to a contemporary date or following tasks are influenced, the construction machines involved within this task are favoured. Therefore a digital deposit of the schedule within the data layer of the control centre is required. The same dynamic allocation using digital Kanban applies to loaded dumpers by dozers in additional consideration of the loaded material.

During the allocation of the Kanban cards it might be determined, that no further dumper is needed at the moment. According to this information the dumper driver may be instructed to forward his pause or will be assigned a parking position. If such a situation occurs and should in fact happen several times, it is possible for the control centre to discover it and inform the construction manager. He can then check if the exclusion of one dumper out of the processes is really possible and, therefore exactly the needed amount of dumpers is in use.

Analogous to this it could occur that an excavator has no available dumper for loading as all of them are busy as they are currently on traffic for example. In this case the driver of the excavator is able to see, when the next dumper will arrive, enabling him to estimate what he could do in the meantime: Depending on the arrival time this might be some extra work in terms of cleaning the excavation borders and refine them or the use of removable multiple dumping beds. This allows the excavator driver to make efficient use of his waiting time.

Correspondingly the construction manager might be informed if, within a certain period, waiting times at excavators occur and therefore the additional use of dumpers may be taken into consideration. In this manner the economic efficiency of the construction site can be improved.

This presented principle of digital Kanban is an artefact of the category of methods in terms of design science research (Hevner et al. 2004). To evaluate the utility of this method, a stochastic simulation will be introduced within the next section.

STOCHASTIC SIMULATION

Simulation in construction is a recognized instrument (Böhnlein 2004, Martinez and Ioannou 1999). It also can be used within the short-term scheduling and project control in the execution phase, allowing a time schedule on a day-to-day or even a task-to-task basis (Hinze 2008).

A stochastic discrete-event-simulation, based on the Monte-Carlo method (Marczyk 1999), is implemented. To generate normal distributed (pseudo) random numbers (Wichmann and Hill 2006) the polar method by Marsaglia and Bray (1964) is used. Construction machines are set up and their performance calculated based on Girmscheid (2010). This data is stochastic varied, so that the filling quantity of the excavator bucket for example is not always the same.

Different layers of earth and chances of incidents can be configured. Directed graphs represent site roads and route planning is calculated by an algorithm developed by Dijkstra (1959). To evaluate the simulation, a simple visualisation shows the ongoing processes and all the results can be saved in a comma-separated values format. This simple but common format is described by Shafranovich (2005). Two different strategies are implemented. On the one hand the currently practiced static variant of dumper allocation and on the other hand digital Kanban - turning the method into an instantiation.

After the simulation passed the verification by module tests and additional calculations, a validation was performed. Therefore a data collection on two construction sites took place, first with a focus at the performance calculation and secondly focusing on the interaction of the construction machines. The data was compared to the results of the stochastic simulation: the validation was also successful. Pretests revealed that 100 runs lead to a statistically significant simulation result.

A construction site with two removal locations and two points of placing, connected by a bidirectional road with a length of 2.5 km, is created. Five dumpers are used at each production line. Figure 3 shows the average results of an eight-hour workday. Presented is the performance Q of the excavators, where the circles represent the currently practiced static variant of dumper allocation ($Q_{ex,\iota}$) and the triangles using digital Kanban ($Q_{ex,\kappa}$).

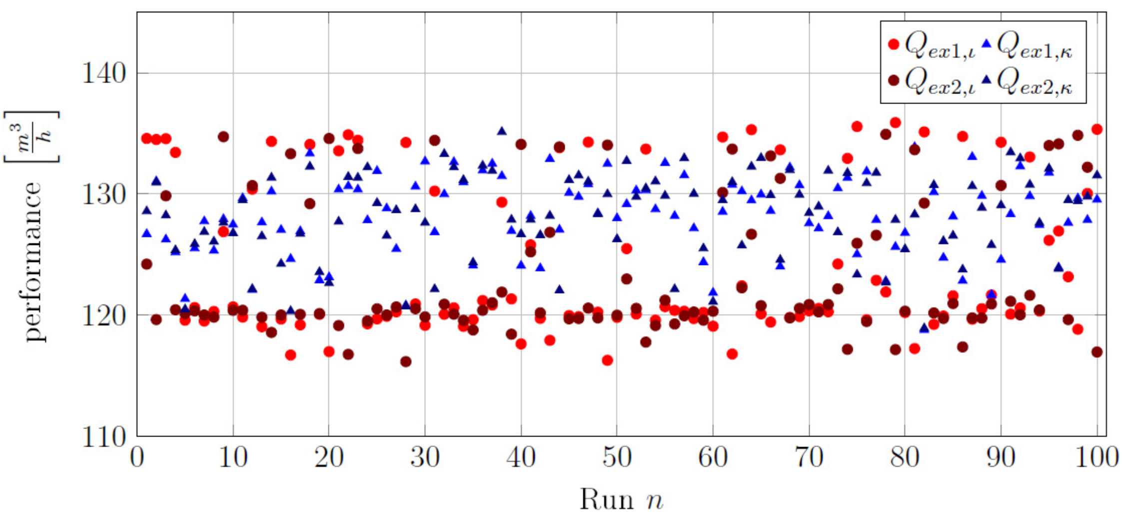

Figure 3: Simulation results: performance

The comparison between the static and the dynamic strategy is shown in table 1. The performance increases by 3.22% respectively 4.05% and the fluctuations reduce when using digital Kanban. This is explained by a more efficient dumper allocation and a minimization of the waiting times as shown in Table 2.

Table 1: Simulation results: performance

construction machine	static (ι) $\left[\frac{m^3}{h}\right]$	dynamic (κ) $\left[\frac{m^3}{h}\right]$	change [%]
$\bar{Q}_{excav_1}$	124.15	128.15	+3.22
σQ_{excav_1}	6.34	3.27	−48.42
$\bar{Q}_{excav_2}$	123.26	128.25	+4.05
σQ_{excav_2}	5.61	3.54	−36.90
$\sum \bar{Q}_{excav}$	247.41	256.39	+3.63
$\sum \bar{Q}_{dumper}$	247.40	256.40	+3.64
$\sum \bar{Q}_{dozer}$	247.40	256.35	+3.62

Table 2: Simulation results: proportionate waiting times

construction machine	static (ι) [%]	dynamic (κ) [%]	change [%]
Excavator 1	9.09	6.09	−33.00
σ_{excav_1}	4.56	2.34	−48.68
Excavator 2	9.69	6.03	−37.77
σ_{excav_2}	4.16	2.49	−40.14
Dumper	13.02	9.85	−24.35
σ_{Dumper}	14.23	6.05	−57.48

In the following the simulation will be extended with the event of a temporary loss of one dumper at the construction site. The results are presented in Table 3. This reveals that due to the missing dumper, the performance of the second excavator is reduced by 12.53% (compare Table and Table 3). The construction site with the incident is marked by a 6.29% lower performance. Also attracting attention is the imbalance between the two excavators. Using digital Kanban a nearly balance excavating performance can be achieved and the performance improved by 5.40% compared to the static strategy. This means that the failure of one dumper results only in a 4.59% rather than a 6.29% reduced performance.

Table 3: Simulation results: performance with incident

construction machine	static (ι) $\left[\frac{m^3}{h}\right]$	dynamic (κ) $\left[\frac{m^3}{h}\right]$	change [%]
$\bar{Q}_{excav1}$	124.27	122.34	−1.55
$\bar{Q}_{excav2}$	107.81	122.28	+13.42
$\sum \bar{Q}_{excav}$	232.09	244.63	+5.40

Figure 4 clearly indicates, how digital Kanban conducts in comparison to the static strategy. The simulation of the construction site is extended with different earth layers and is using a growing amount of dumpers. It is shown, that a certain scope of numbers exists (in this case, approximately seven to thirteen dumpers), in which digital Kanban can take its advantage. The amount of dumpers beneath this area is so low that no difference in the overall performance exists. Also a difference above this area cannot be found, as from a certain amount of dumpers an oversupply of dumpers exists and therefore all waiting times of the excavators are eliminated. A use of this high number of dumpers however is uneconomic, as the dumpers spend most of their time waiting. It is also shown in Figure 4, that digital Kanban leads to at least as good results as the static strategy.

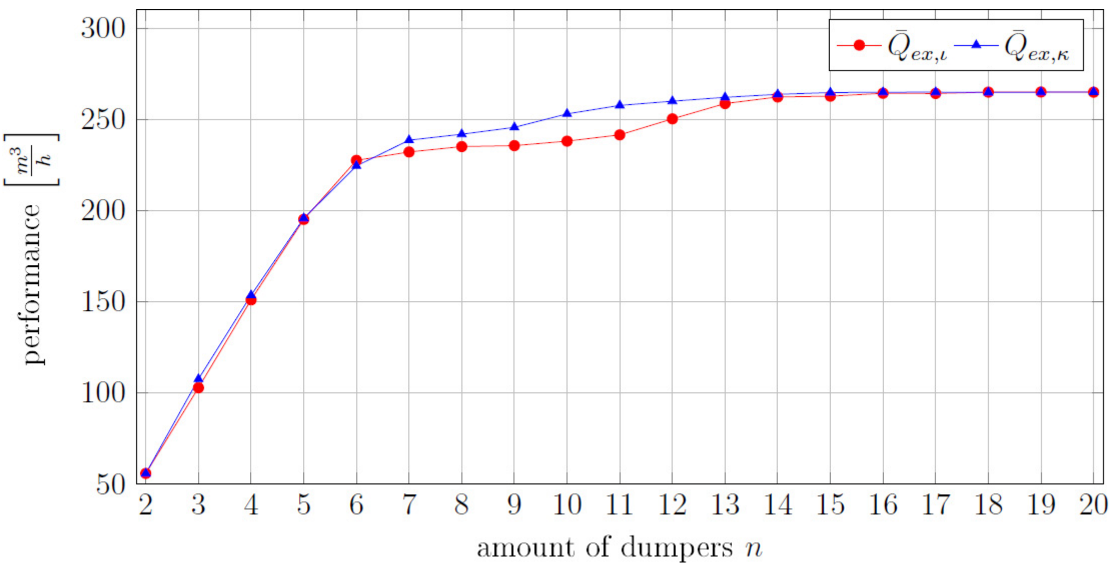

Figure 4: Performance depending on the amount of dumpers

CONCLUSION

There is a significant potential of improvement at most construction sites. Especially earthworks are characterized by huge dynamics and uncertainty. The successful use of information systems as well as modern communication techniques in the stationary industry and the profitable application of lean management methods in construction promises in combination a more efficient and effective design of earthworks processes.

This paper presents a new method, digital Kanban, to dynamically adapt the allocation of transport vehicles in the earthwork process by using a flexible Kanban system, supported by the use of machine sensory and information technology.

Quantitatively the effects of digital Kanban could be shown based on stochastic simulations. In comparison to the currently used static variant of dumper allocation, a reduction of variance, and therefore increased process reliability can be achieved by applying digital Kanban. The minimized waiting times of not only excavators but also dumpers and dozers result in an increase in performance. This leads to a reduced operating time of the construction machines, which enables the possibility of an earlier use of this construction machines at another construction site. Therefore cost effectiveness and performance will be enhanced. According to the research method of design science research the utility of the develop artefact, the implementation of digital Kanban, could be proved.

Summarizing this work so far, it can be concluded, that the use of a construction site control centre for earth work and therefore the connected application of some lean management principles, especially Kanban, is very promising and presents a great opportunity for improving processes in future work on earthwork construction sites.

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