Model in the loop simulation towards the development of a smart fleet management system

Amadeusz Kargul, kargul@fml.mw.tum.de
Institute for materials handling, material flow, logistics, Technische Universität München, Germany

Sebastian Rehberger, rehberger@ais.mw.tum.de
Institute for Automation and Information Systems, Technische Universität München, Germany

Stanislav Chuyev, stanislav.chuyev@tum.de
Graduate Student, Technische Universität München, Germany

Willibald A. Günthner, kontakt@fml.mw.tum.de
Institute for materials handling, material flow, logistics, Technische Universität München, Germany

Birgit Vogel-Heuser, info@ais.mw.tum.de
Institute for Automation and Information Systems, Technische Universität München, Germany

Abstract
In recent years the need for the exchange and aggregation of process information at a construction site with the goal to enhance the site productivity has emerged. The collected machine data supports the relevant decision makers with viable information about the current state of the construction site. In the approach a method is surveyed for capturing and processing field data from different operation cells on site by the use of a Model-in-the-Loop (MiL) simulation. Models of data collectors, the so-called telematics units, are coupled to the machine entities in a discrete-event-simulation (DES), simulating a construction site and its corresponding operation processes. Finally, the framework is evaluated by finding the suitable data transfer rate between the telematics unit and a central decision-making logic for increasing the efficiency of an excavator-truck operation chain.

Keywords: model-in-the-loop simulation; construction equipment; telematics; machine communication,

1 Introduction
Heavy construction operations in civil engineering are characterized by the use of various types of construction equipment. The success or failure of a project regarding cost and time depends mainly on an effective and efficient use of the construction equipment (Song & Eldin 2012). Nevertheless, the current process control on construction sites can be described as an inflexible rigid system, where construction machinery represent self-sufficient tools that maintain little or no exchange among each other. This results in merely isolated operation cells within successive building process chains (Hubl et al. 2015).

In this paper a method for evaluating communication between an on-board telematics unit on a construction vehicle with further end points is discussed. Two communication topologies are relevant in this context. The first is the horizontal communication between the vehicle and another machine, usually described as machine-to-machine (M2M) communication. The second category is the communication between the vehicle and a back-end, consequently a personal computer in the company for accessing its current state data.

This machine-to-office (M2O) communication is widely employed in the field of process control. In this case field data from the construction machinery is evaluated in the back-office with the goal of deriving optimization measures for the process chain.

The presented approach focuses to offer a MiL environment which enables to analyze the effect of communication between construction entities with the goal of optimizing the underlying operation chain. Following this results, the authors derive requirements for the communication architecture. The architecture consists of a telematics unit in each machine and a central server for data aggregation and information routing between the system entities. Due to the model representation and effect analysis, the requirements for the real hardware and software architecture of the telematics unit are derived.

The paper is structured as follows. First there is an overview of the related work in the field of smart construction sites. Chapter three describes the general framework of the presented work focusing the interaction between the MiL simulation and the DES. In chapter four the MiL framework is evaluated by simulating the effects of different data transfer rates and their impact on the process efficiency. Finally, chapter five gives a conclusion of the work and an outlook for the further development of the framework.

2 Literature review

The current research aims to enable *Smart Construction Sites* with focus on capturing as-built data, processing the data and support the decision-making process of the responsible stakeholder based on the information obtained (Hammad et al. 2012).

For evaluation purposes, there are different methodologies to represent the behavior of a real engineering system on-site where real-time data collecting, processing and smart decision-making take place. For field data capturing, there are often conducted laboratory scale experiments with miniature models of the construction equipment provided with different tracking sensors (Akhavian & Behzadan 2012, Hammad et al. 2013, Vahdatikhaki & Hammad 2014). Further efforts are evaluations with capturing and processing field data (in real time or near-real time) from real construction environments (Song & Eldin 2012, Pradhananga & Teizer 2013). The following data evaluation takes place in DES where decisions from a supervisory logic (e.g. a Multi-Agent System (Zhang et al. 2009, Kim & Kim 2010)) are verified in order to investigate their impacts concerning improvements of the overall project performance and/or resource allocation to enable a smart site environment (Xie et al. 2011, Akhavian & Behzadan 2014, Horenburg et al. 2012). Thus, the question remains how often the field data is sent to a database for further decision-making in order to specify the requirements for an enhanced communication unit on board of the construction equipment.

In comparison to the construction industry, the engineering process in the automotive industry already had to cope with a rigorous rise of quantity and complexity of information and communication technologies (ICT) in vehicles (e.g. driver assistance). Further communication with external service providers has been introduced (e.g. navigation, traffic information) and standardized. This leads to a high system complexity with several on-board control units, which are communicating via a bus system. A common method for designing such systems in an early product phase is the use of Model-, Software- and Hardware-in-the-Loop approaches. (Isermann et al. 1999) surveyed the use of Hardware-in-the-Loop for the development of engine control units (ECU). The authors came to the conclusion that the use of real-time simulation is inevitable for cost- and time-efficient development of such systems. (Kendall & Jones 1999) conducted a similar study with the conclusion that “pure” simulation as a first step forces a better understanding of the system behavior during an early design phase. MiL represents a combined simulation of a model plant and a concurrent control algorithm which are executed in a single simulation environment without real-time constraints. (Gietelink & Ploeg 2006) give a V-model for the development process of automotive safety-critical systems. Herein, MiL is used during the left part of the V-model for deciding on functional requirements, system specification and finally constructing modules for the example of a driver assistance system.

3 General framework

The research bases on two simulation environments. The interaction between several entities in a work chain of a construction operation is realized in a DES. Thus, this represents the overall workflow within the operation chain. The MiL environment is embedded in the DES. Each discrete event during the interaction of two entities in an operation cell (production cell or transportation cell) activates the MiL where the field data is captured, preprocessed and transmitted by the communication layer.

The process data is then transmitted to the database of a fleet management system (FMS). In the back-end the data obtained from the different cells need to be processed to key performance indicators (KPI) which describe sufficiently the current situation on site. A business intelligence logic within the FMS decides if the current situation (e.g. performance, resource allocation) need to be replanned and communicated to the responsible stakeholder on site. The paper focuses two parts of the presented framework which are described in the following. Figure 1 shows the workflow of the described framework.

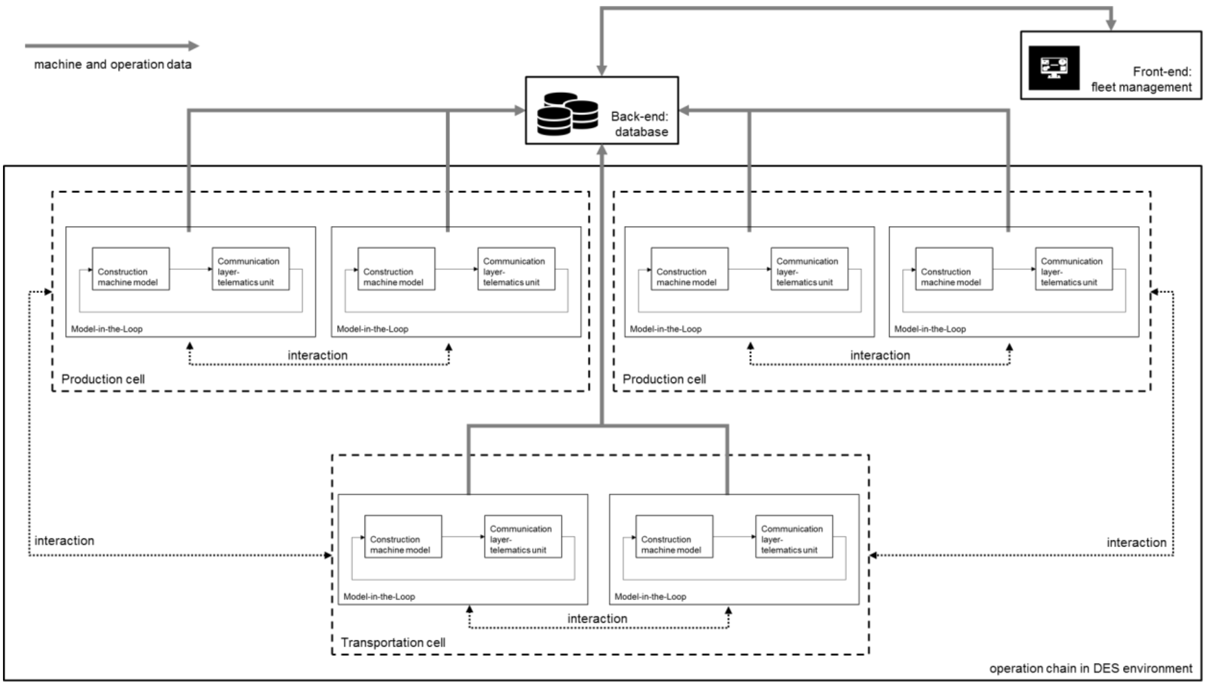

Figure 1: Research framework

3.1 DES

An operation chain in heavy equipped construction sites with different production locations can be broken down in several production cells where different machines are working independently in a dependent operation chain. Between these cells the material flow is carried out by the supply logistics (transportation cell) which connect the productions cells. These supply entities depend from the performance of the production cells in the operation chain.

All operations represent repetitive work tasks which can be modeled as discrete activities in a DES. In the case we use the simulation environment Plant Simulation. The general structure of the DES allows that n-production cells can interact with n-transporation cells to represent all kinds of site environments. Production cells can be further adapted to different work contents (e.g. earth works, pavement works, etc.).

3.2 MiL

As discussed in the related work, using MiL as a design method supports the derivation of hard- and software requirements during product development with the support of simulation.
Therefore a method for the simulation of the telematics logic, its communication interfaces and properties to analyze the resulting process chain efficiency is proposed. In figure 2 the

setup for the MiL approach is shown, which poses a sufficient system description with closed-loop behavior, offering to evaluate the interaction between plant, logic and a central directive (e.g. an optimization algorithm).

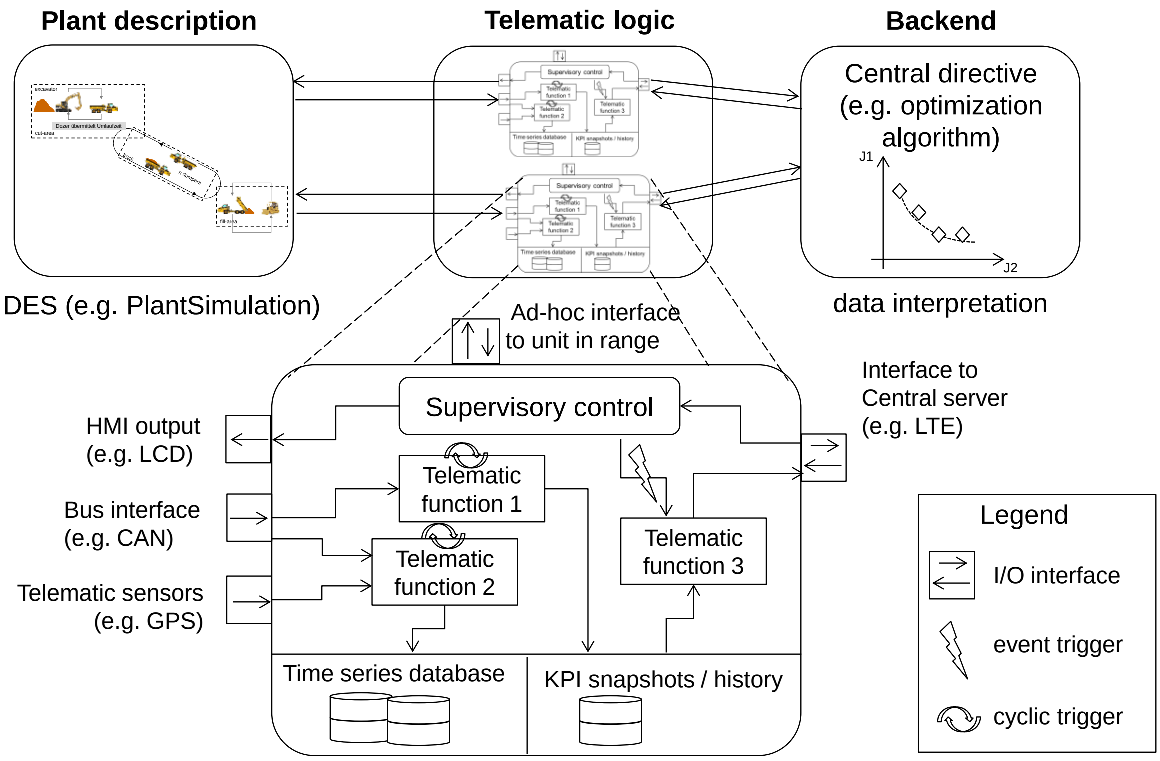

Figure 2: Description of the MiL process

For the construction site the existence of a plurality of operation cells, truck entities as well as transferable material in the model is assumed. The truck entities are connecting different production cells and establish the material flow through the system model. There is further assumed that a driver/machinist is existent who receives information from the environment and from other model entities via the telematics unit. This person will carry out tasks in accordance to the transferred information and without any uncertainties. A suitable simulation environment for a MiL experiment is the above mentioned DES, since no continuous information (e.g. hydraulic pressure) is needed on this abstraction level.

For the telematics unit the model of a control system is designed, which possesses functions for evaluation, storage and data transfer of information between the system's participants. The handled machine information is aggregated to key performance indicators (KPI) for further processing. The communication pathways implemented between different telematics units or between one unit and a central server are essential in this model. Time series' of machine data are collected from arbitrary signals on board of the machine, stored locally and possibly processed in combination with other time series and sensor data (e.g. GPS) to calculate a respective KPI (e.g. performance). The generated KPI data structure is also stored with a time-stamp. The KPI matrix is then sent to a central server in predetermined transfer rates. This represents a model-in-the-loop approach, since the control logic of the system-under-test (SUT) is not programmed in a target programming language but is formulated as an executable model (e.g. a finite state-machine) at this design stage. The communication of KPI's and data is constructed within this model to survey different communication topologies (e.g. star topology with a server) as well as the resulting behavior when communication uncertainties (delay, jitter, e.g.) are present (Cervin et al. 2003).

In the case of a telematics function that provokes a response from the server, e.g. a directive for the machine driver, the MiL will behave as a closed-loop system. Two different transfer methods are implemented, an event-triggered as well as a cyclic triggered execution (e.g. to push uploading of data). Both trigger may be influenced autonomously by the local telematics supervisory control or are preconfigured remotely by a back-office user. Thus, the resulting effect of a newly implemented telematics function on the process (e.g. the KPI's) will be observable in a MiL simulation experiment. The result supports the decision for the hard- and software requirements of a telematics unit and gives insight about its trade-off for the process efficiency. Further the need and benefit of additional communication interfaces (e.g. Wi-Fi) will be evaluated and specified.

4 Test case

The main research question of the presented work is to investigate the impacts of different data transfer rates for the operation chain. After each data exchange, the server supervises the current performance in order to adapt, if necessary, the current allocation of the transport entities (trucks).

The test case consists of three different production cells linked together via two transportation cells where the material flow between the predecessor cell and the two successor cells takes places. Route one leads to the successor (dozer) on site and route two to a successor out of the site with different cycle times. Thus, the excavator in the cut-area loads soil onto the current number of trucks. The trucks transport the soil either to a fill-area on site where a downstream machine in the chain processes the material or to a fill-area out of the site where the remaining soil is disposed.

The assumptions of the processing times (loading, hauling, dumping) within the cells are based on real-world values. Due to the dynamic nature of construction site, malfunctions of the construction equipment also need to be considered and are represented as probability of the machine availability and mean-time-to-repair based on empirical values. These assumptions represent the volatility of the construction process. Figure 3 shows the operation chain with the different production cells involved.

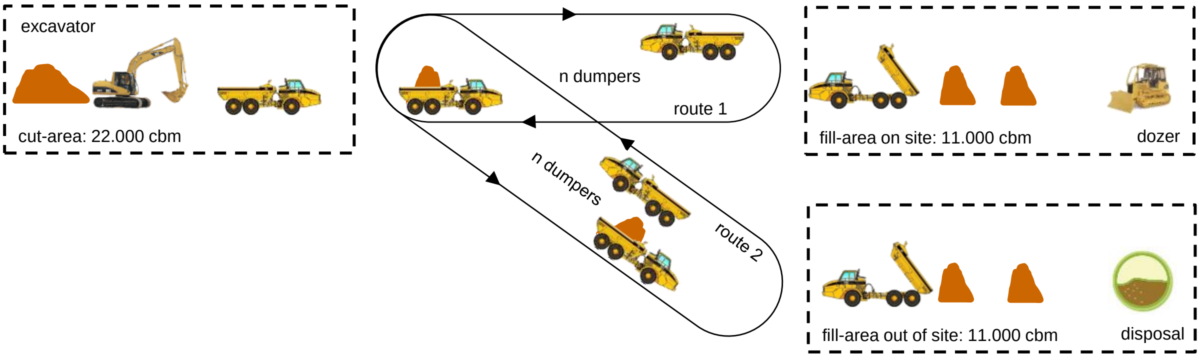

Figure 3: Set-up of the case study

Table 1 shows the KPI that are processed with presented DES and MiL environment.

Table 1: KPI measured in defined cycle times

entity	KPI	description
production cell [1-3]	performance [m³/h]	quotient of material processed in the production cell to an hour
	waiting time [%]	time percentage in which the production cell was not active (processing)
	throughput time [min]	time between start loading in fill production cell and end unloading in cut production cell
transportation cell [1-2]	performance [m³/h]	quotient of soil hauled to a specific time period
	waiting time [%]	waiting time in queues of the production cells
	number of trucks [#]	current number of trucks in the system designated to each sink

Based on the KPI's the decision-making logic considers to reallocate (add, remove or keep) trucks designated to the different production cells in every algorithm iteration. The target function performs a maximization of the production output rates (performance of production cells). For this purpose the current output rates of the production cells are compared to the values of the previous period. If a change in performance can be assigned to an increase (decrease) of the trucks number in the previous period than this impact is analyzed in the following way. The actual change of the production cell output (ΔTH) is compared to the maximal possible throughput of trucks added to the system or taken out of that (ΔC). If this rate does not exceed a defined threshold value (x) the impact of the truck addition (deduction) will not be significant as it does not sufficiently contribute to the system performance (ΔTH / ΔC < x).
This logic allows to reach a number of trucks ensuring a high output level but not to introduce additional transportation units when the curve, shown in figure 4, becomes flatter.

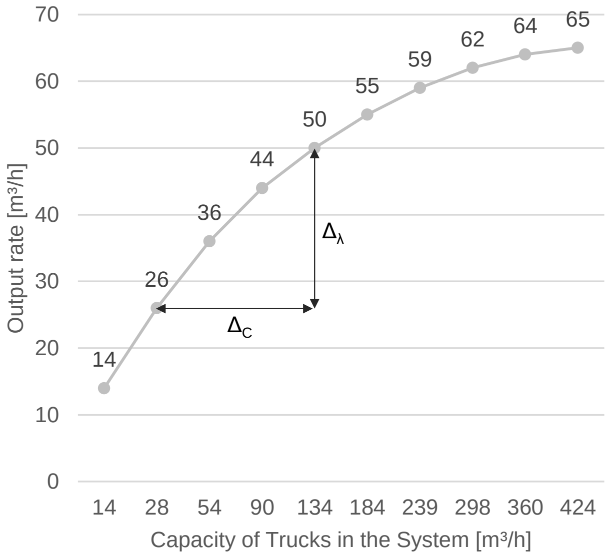

Figure 4: Typical Dependence between installed trucks capacity and production output (exemplary numbers)

The output optimization takes place under an additional constraint preventing the waiting times of the transportation cells increasing disproportionately. The constraints is implemented in order to avoid truck queues in front of the production cells that can occur due to output maximization. In such a case no additional trucks can be added into the system.

Seven experiments with different data transfer rates are conducted with 100 observations for each simulation run.

4.1 Discussion

It is evident that interventions in shorter transfer rates lead to an increase of the overall performance. Nevertheless, the proposed work shows a tendency to what extent a shorter data transfer rate make sense in order to have a positive effect on the overall performance. Figure 5 shows the results of the conducted experiments with box-plots.

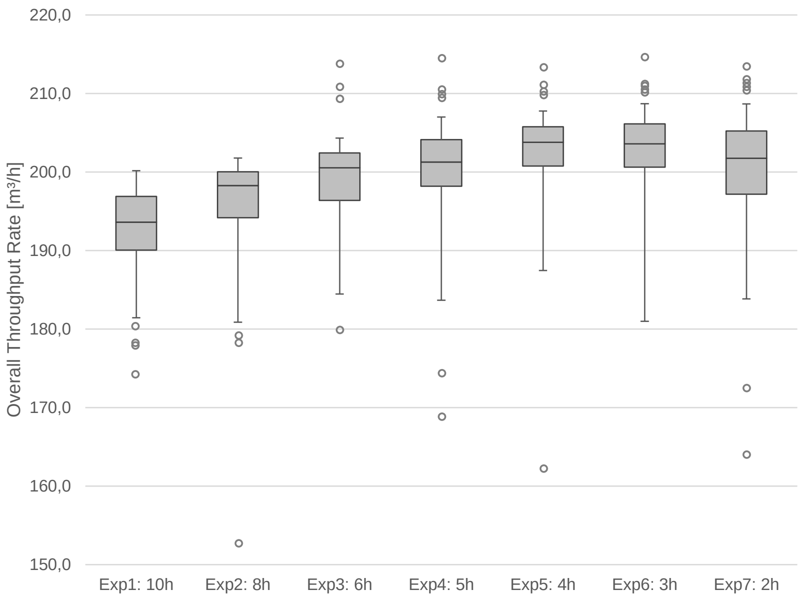

Figure 5: Experiment results of the different data transfer rates

The best throughput rates were achieved with shorter data transfer rates in the range between three and four hours. The overall throughput rate of the entire operation chain reaches the best results for Exp5: 3h 203,8 m^3/h and Exp6: 5h 203,6 m^3/h. Compared to the worst value (Exp1: 10h 193,6m^3/h), there is a significant improvement of 5,2% and confirms the assumptions to follow shorter transfer frequency.

The results offer the insight that the proposed framework is viable, but more experiments have to be conducted to analyze trade-off effects under the influence of uncertainties in the simulation. It is necessary to evaluate more allocations of the production and transportation cells with a higher complexity (also with different work contents, e.g. pavement works). Another question to be investigated is to what extent changes within the decision-making logic affect the results and consistently the data transfer rates.

5 Conclusion

Different data transfer rates have been investigated in order to evaluate to what extent data transfer rates of the current project performance are effecting the described DES and MiL environment. Therefore a supervisory logic investigated for each data transfer rate, if necessary, to reallocate the current entities within the transportation cells. Frequent data transfer rates lead to an increase of the communication between the different operation cells. “Connecting” these cells via a supervisory logic enable them to understand their behavior and the behavior of their predecessor and successor. Thus, they are able to match their activities with its neighbor cells to approximate an optimal operating point for the overall operation chain.

The next steps consist in evaluating further requirements of the telematics unit. A further question from the operational point of view is the possibility that several telematics units of the construction equipment are communicating directly on site without transmitting field data to a central directive to enable a machine-to-machine communication. Therefore, as the next development step, a transfer of the developed method to a Hardware-in-the-Loop (HiL) environment with physical telematics units will be conducted to generate a real data transmission for further evaluations. Finally, the telematics unit will be implemented prototypically in real construction machines after finalizing all necessary use cases in the discussed simulation framework.

6 Acknowledgement

The collective research project 18135 N/1 of the research association Bundesvereinigung Logistik e.V. – BVL is funded by the AiF within the Industrial Collective Research Program (IGF) by the German Federal Ministry for Economic Affairs and Energy on the base of a decision by the German Bundestag.

References

AKHAVIAN, R. & BEHZADAN, A. H. (2012). An integrated data collection and analysis framework for remote monitoring and planning of construction operations. *Advanced Engineering Informatics,* 26**,** p. 749-761.

AKHAVIAN, R. & BEHZADAN, A. H. (2014). Evaluation of queuing systems for knowledge-based simulation of construction processes. *Automation in Construction,* 47**,** p. 37-49.

CERVIN, A., HENRIKSSON, D., LINCOLN, B., EKER, J. & ÅRZÉN, K. E. (2003). How does control timing affect performance? *IEEE Control Systems Magazine,* 23**,** p. 16-30.

GIETELINK, O. & PLOEG, J. (2006). Development of advanced driver assistance systems with vehicle hardware-in-the-loop simulations. *Vehicle System Dynamics,* 44**,** p. 569-590.

HAMMAD, A., VAHDATIKHAKI, F. & ZHANG, C. (2013). A novel integrated approach to project-level automated machine control/guidance systems in construction projects. *Journal of Information Technology in Construction,* 18**,** p. 162-181.

HAMMAD, A., VAHDATIKHAKI, F., ZHANG, C., MAWLANA, M. & DORIANI, A. (2012). Towards the smart construction site: improving productivity and safety of construction projects using multi-agent systems, real-time simulation and automated machine control. *Proc. of the Winter Simulation Conference*. Berlin, Germany, 09th-12th 2012. p. 404.

HORENBURG, T., WIMMER, J., GÜNTHNER, W. A., DORI, G. & BORRMANN, A. (2012). Towards collection, processing and use of actual data for process simulation during construction. *Proceedings of the International Workshop: Intelligent Computing in Engineering 2012*. Herrsching, Munich, Germany. p. 789-799.

HUBL, M., MUELLER, M. & MERKERT, J. (2015). Coordination of Just-in-Time Deliveries with Multi-attribute Auctions. *Proceeding of the 12th International Conference on Wirtschaftsinformatik 2015*. Osnabrück, Germany. p. 91-105.

ISERMANN, R., SCHAFFNIT, J. & SINSEL, S. (1999). Hardware-in-the-loop simulation for the design and testing of engine-control systems. *Control Engineering Practice,* 7**,** p. 643-653.

KENDALL, I. R. & JONES, R. P. (1999). An investigation into the use of hardware-in-the-loop simulation testing for automotive electronic control systems. *Control Engineering Practice,* 7**,** p. 1343-1356.

KIM, K. & KIM, K. J. (2010). Multi-agent-based simulation system for construction operations with congested flows. *Automation in Construction,* 19**,** p. 867-874.

PRADHANANGA, N. & TEIZER, J. (2013). Automatic spatio-temporal analysis of construction site equipment operations using GPS data. *Automation in Construction,* 29**,** p. 107-122.

SONG, L. & ELDIN, N. N. (2012). Adaptive real-time tracking and simulation of heavy construction operations for look-ahead scheduling. *Automation in Construction,* 27**,** p. 32–39.

VAHDATIKHAKI, F. & HAMMAD, A. (2014). Framework for near real-time simulation of earthmoving projects using location tracking technologies. *Automation in Construction,* 42**,** p. 50-67.

XIE, H., ABOURIZK, S. & FERNANDO, S. (2011). Integrating realtime project progress input into a construction simulation model. *Proceedings of the Winter Simulation Conference 2011.* Phoenix, United States, 11th-14th December. p. 3443-3454.

ZHANG, C., HAMMAD, A. & BAHNASSI, H. (2009). Collaborative multi-agent systems for construction equipment based on real-time field data capturing. *Journal of Information Technology in Construction,* 14**,** p. 204-228.