INTRODUCTION OF A DIGITAL EARTHWORK CONSTRUCTION SITE

Kim Kirchbach[1], Dominik Steuer[2] and Fritz Gehbauer[3]

ABSTRACT

The concept of the "digital factory" has already been successfully implemented in the automotive and manufacturing industry. An adaption, following lean principles, to the construction site seems promising. Combining sensors, information technology, and approaches of Building information modeling (BIM) allows a cross-linking of construction machines and therefore offers a higher level of information transparency. This enables construction machines a faster way of discovering changes through the dynamics of the construction process (change of soil class, weather conditions, etc.).

Higher transparency and reduced waste can lead not only to a higher utilization of one construction machine but also to a higher efficiency of the whole process chain by the related lean management methods. The collected information can also be used for a new and dynamic type of allocation of the construction machines based on a flexible Kanban system. An improved constructive cooperation and coordination (e.g. reduced waiting or unproductive times) ensures that potentials will be exploited and a value maximization achieved.

This paper will show a theoretical model, based on expert interviews and stochastic simulations. It provides an estimation of the implementation cost and running expenses in comparison with the mentioned potential for optimization.

KEYWORDS

Lean Construction, IT in Lean, standardization, visual management, Last Planner System

INTRODUCTION

Methods like Target Value Design and the Last Planner System are well developed and tested in the construction sector (Adamu and Howell 2012, Hamzeh et al. 2008, Zimina et al. 2012). To get the maximum outcome from these methods, valid data within the process chains is needed. The complex environment of an earthwork construction site leads to a lack of valid reliable data about the whole process chain (Kirchbach et al. 2012). Therefore companies and workers on those sites are headed towards uncertain situations, which cannot be handled properly with the common

1 Research Fellow. Karlsruhe Institute of Technology (KIT), Institute for Technology and Management in Construction, Am Fasanengarten, Geb. 50.31, 76131 Karlsruhe, Germany, Phone +49 721 60848223, kim.kirchbach@kit.edu

2 Graduate Student. Karlsruhe Institute of Technology (KIT), Institute for Technology and Management in Construction, Am Fasanengarten, Geb. 50.31, 76131 Karlsruhe, Germany, dominik.steuer@student.kit.edu

3 Professor. Karlsruhe Institute of Technology (KIT), Institute for Technology and Management in Construction, Am Fasanengarten, Geb. 50.31, 76131 Karlsruhe, Germany, Phone +49 721 60842646, fritz.gehbauer@kit.edu

push-based project management and production planning tools. The use of the right IT-systems can change this. Computer integrated construction enables a link between the design, construction and inspection phases by using real-time process data (Jonasson et al. 2002). In the stationary industry the use of modern communication techniques, like Material Requirements Planning (MRP), Enterprise Resource Planning (ERP) or Customer Relationship Management (CRM)-Systems is standard and has long been used with great success (Brynjolfsson and Hitt 2003). As these kinds of systems are depending on constant production systems and the construction process is highly fragmented and complex in comparison (Akinsola et al. 2000).

Earlier research has shown that the use of information and communication technology (ICT) on a constructions site can lead to higher "Percent Plan Complete" rates (PPC) (Sacks et al. 2010). With a total integrated system these effects should become more obvious not only in the stationary but also in construction industry. Thus leads to the following hypotheses:

1. Using Information and Communication Technology on an earthwork construction site fosters the usage of lean methods.
2. The investment in those technologies optimizes the costs.

The chosen research methodology combines a literature analysis with several expert interviews. The figures, which are the basis for later calculations, are taken from these interviews, the German construction equipment lists (Central Federation of the German Construction Industry 2007) and the German Federal Statistical Office (Federal Statistical Office 2010, Federal Statistical Office 2012). The figures are also supported by stochastic simulations. This paper presents an approach, which combines BIM, machine control technology and mobile devices to become an integrated production planning tool. In the following paragraphs the technologies for this approach are introduced. The expected costs are presented and the connection between technology and lean methods is built.

BIM – BUILDING INFORMATION MODEL

BIM is "the basis for new construction capabilities and changes in the roles and relationships among a project team. When implemented appropriately, BIM facilitates a more integrated design and construction process that results in better quality buildings at lower cost and reduced project duration." (Eastman et al. 2008) To achieve these aims, BIM combines 3D building models with time, cost, and quality schedules also known as 6D models. Even though the management method of lean thinking and the information technology of BIM can be seen separately it seems to be more efficient to use BIM in conjunction with integrated project delivery (IPD) (Eckblad et al. 2007). The use of BIM or so called "computer advanced visualization tools" has led projects to waste reduction, improved working flow and a more customer centred value generation; all of them are used to be mentioned in the application of lean thinking (Fernández-Solís and Mutis 2009). Despite that, the main issue in which BIM does not fit into the lean construction site is the huge amount of information, which is carried around while creating and using it. Having this huge amount of data at hand might lead to higher complexity and to more difficulties in the process of decision making (Sacks et al. 2010). So far the impact of this data complexity on the success of the construction site has to be proved and until then as much (helpful) data as possible is required.

To investigate in this matter, interviews with an international active construction company have been held. Their experience shows that the use of BIM could and should lead to the standardization of planning processes, providing a potential up to 20% time savings during the planning phase. Despite the fact that whole projects are not as easy to standardize, the efforts made in the planning phase are a success as they lead to a reliable model, which could later be used for visual construction site simulation. So in regards to the main concept of lean, the production process could be simultaneously designed to the building itself. This offers the opportunity of spotting possible interruption before the first machine started on the site therefore the alteration in the project could be done at a lower level of changing costs.

The costs for implementing a BIM system to a company on the other hand are difficult to measure, because it is more of a process and not a radical change. Today only a few projects were consequently planned and executed with BIM, mostly high complex buildings like hospitals are planned this way (Lostuvali et al. 2012). According to interviewed experts, producing and working with BIM software, their first experiences with BIM are very promising and they plan its further use. In terms of costs the experts mention that the use of BIM software is a process of at least one and a half years with constant training plus the costs for the software.

MACHINE CONTROL AND FLEET MANAGEMENT TOOLS

Since the 1990s construction machines like excavators, graders and dozers can be equipped with different machine controls (Stempfhuber 2006). These control techniques link the machines to 3D digital terrain models through which for example the machine operator can see the working progress in real-time on a screen in his machine. This helps to reduce overwork and waste because the operator is fully aware of his task by the visualization (Jonasson et al. 2002). Studies have shown that by using this kind of control there is an increase in efficiency between 20-30% per machine (Adhalsteinsson 2008). These numbers can be confirmed by interviews with sensors developers regarding their trainings measures. Its results in the delivery of better quality due to more accurately excavated or graded terrains and higher productivity. Nowadays most of the large construction companies are using this technology for selected machines, especially when precise surface grades are needed.

To implement the digital earthwork construction site it is necessary to equip all machines used on the site with several sensors: 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 and technical data like maintenance intervals, amount of diesel or engine oil pressure. It does need to be analysed whether all machines are to be equipped with the whole sensor system or if in some cases of earthwork it is enough to just make the machines trackable. In any case the sensor equipment is necessary to collect and use data, making a continuous improvement process possible. According to interviews with experts, developers and producers of those sensors, the technology is ready for use but the market penetration is low. One reason for this are the equipment costs which vary between 35,000 € and 60,000 € depending on machine type and producer. The costs related to repair and maintenance of the sensors are negligibly small. In context of lean thinking and the comparison to the digital factory, these technologies can be used to improve the overall process chain of an earthwork construction site.

Mobile Devices and Construction Control Center

It has already been recognized that the use of mobile devices provides the opportunity for improving the information flow at construction sites (Bowden et al. 2006). Also Augmented Reality, a human-computer interface which combines the real world with context-sensitive information presented by virtual overlays, has been recommended (Shin and Dunston 2008). The use of these techniques can play an important role in the field of “Visual Management” (Tezel et al. 2009) leading to a higher level of transparency. (Kirchbach and Runde 2012)

As described in Kirchbach et al. (2012) a construction site control center, based on the methods of Virtual and Augmented Reality, can be the foundation for optimized construction site logistics especially to adjust truck disposal. The easy visualization reduces the mental load of the user and allows a faster detection of root causes for errors to induce a continuous process improvement system.

COMBINING TECHNOLOGIES TO ENABLE LEAN MANAGEMENT

By using BIM software a construction model is planned. This model contains all necessary information such as geometric data and process models, enabling the development of the product and the production process simultaneously. Simulation tools and the earlier described Augmented and Virtual Reality technologies allow the visualization of the construction site. It now also becomes possible to detect clashes before the first construction machine has even started its work on the site. This has the effect that the correction of bad planning becomes much cheaper. A communication platform enables a construction site wide information exchange, especially between the machine teams, leading to a digital earthwork construction site (compare figure 1 and (Kirchbach et al. 2012)). As presented in figure 1 the project manager has got the opportunity to get real-time and target-actual comparison of the construction process in the presentation layer. This is based on a logical layer, which combines the BIM model via a communication platform with the machines and their (performance) data. Additionally the data layer offers supporting information, like empirical values throughout the project and older projects.

The machine teams have the possibility to partly organize themselves, providing that disturbances can be handled and maybe even solved on the machine level before they are passed on to the control center and thus to the project manager. For example a typical disturbance can be an unexpected change of the soil class, leading to a change in the performance of an excavator so that more or less transport vehicles are needed. In case that the machine teams cannot handle a problem themselves, suggestions for process adjustments are generated automatically and presented to the site manager in the control center. These suggestions are the result of the simulation of possible new schedules, based on the planning model and other information like machine data from die project databases.

The complete system with the communication platform can then dynamically allocate the best possible match of excavator and transport vehicles using a Kanban-like system, where excavators pull empty trucks and dozers pull loaded truck. After dumping an empty truck will be pulled by an excavator. If more than one excavator requests a truck, the systems analyses the current performance of the excavators, their current allocated trucks and the distances to be travelled and prioritize the Kanban cards in order to optimize the productivity of the whole construction site. Same applies to loaded trucks by dozers but additional in consideration of the loaded material.

Another benefit is the continuous flow and availability of information. The complete system provides high data transparency and therefore the opportunity to make reliable decisions based on actual performance data. This assured data basis relieves the construction manager leading to an expected increase in efficiency. By this reasoning and the previous sections, on the basis of interviews and a literature review, the first hypothesis, information technology fostering the usage of lean methods, can be preliminary considered as validated.

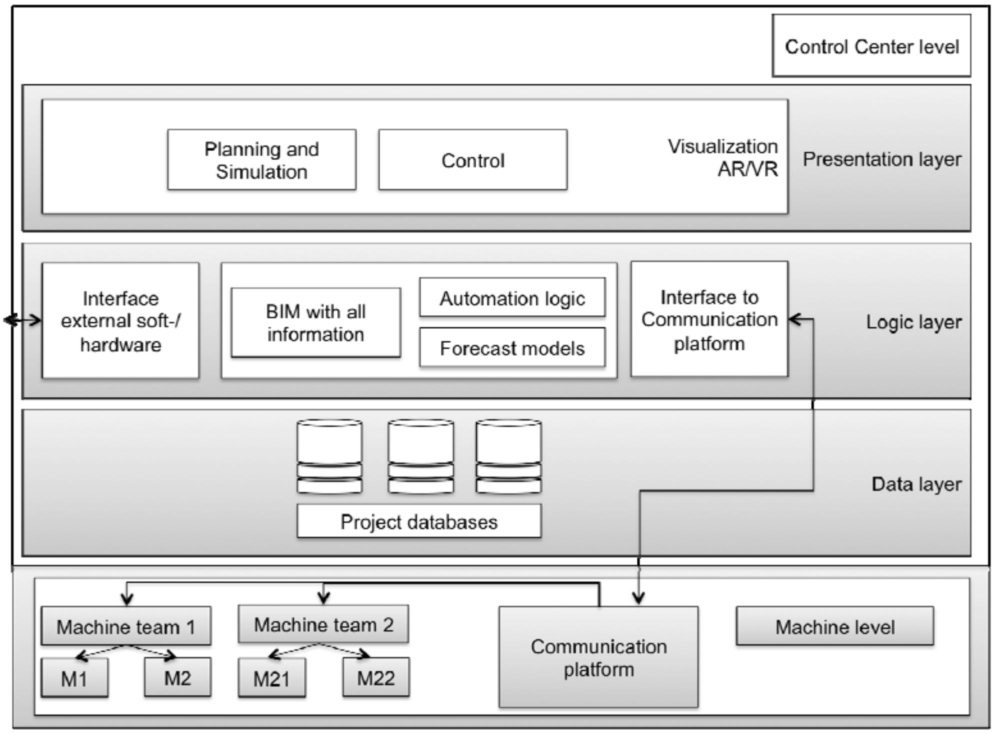

Figure 1: Combination of BIM, machine sensors and visualization tools

COMPARISON OF DIGITAL CONSTRUCTION AND TRADITIONAL SITE

Return on invest is the crucial measure for the construction industry when investing in such a technology. The following paragraph compares the production performance of a simple earthwork process regarding differences in lead times and machine costs. In Table 1, a middle-sized excavator with 160 kW motor power and 26,800 kg weight is being taken as the use case.

To get a reliable performance comparison the applicable indicator has to be used which in this case is the performance per hour; it is also used to spot bottlenecks in a process chain. The following assumptions are based on German construction equipment lists (Central Federation of the German Construction Industry 2007). Regarding this list the excavator described has a total provision of 65 months and every month has 170 hours of provision. These hours include downtimes, moving time, repair time and operating time, basically the amount of time when the machine cannot be used elsewhere (Girmscheid 2010). To spot the impact of the system, described in this paper, it must be differentiated between machines without sensors or with sensors and machines, which are used in a completely connected environment.

Table 2: Costs for a medium size excavator

Acquisition costs in Euro	Without sensors	With sensors	Complete system
Machine	245,500 €	245,500 €	245,500 €
Sensors		45,000 €	45,000 €
Communication platform			4,000 €
Total	**245,500 €**	**290,500 €**	**294,500 €**

Table 2 derives the cost per cubic meter of excavated soil from cost per hours and compares them in the above described use cases to identify the needed increase in performance. It is being assumed that the new technology needs to have at least the same price per cubic meter. So the information given in table 2 regard the needed performance per hour marks the break-even point.

Table 3: Costs per hour and needed performance per hour

	Without sensors	With sensors	Complete system
Cost per hour	22.22 €	26.29 €	26.65 €
Cost per cbm	0.54 €	≤ 0.54 €	≤ 0.54 €
Needed Performance per hour	40.80 cbm	≥ 48.27 cbm	≥ 48.93 cbm
Needed increase in Performance	-	≥ 18.3 %	≥ 1.7 %

The calculations revealed that a productivity increase of 18.3 % from non-equipped machines to sensor-equipped machines is necessary and the additional performance increase to use the complete system is at 1.7 %. Researchers at the Reykjavik University found that, using a simple trench construction work, the excavator saved 22.93 % of time (Adhalsteinsson 2008), which shows that the increase in productivity from non-sensors to sensor-equipped machines is very realistic. It also means less working hours, leading to lower running costs. This technology enables a company to reduce provision time and the machine is available for other projects much faster. Another important aspect is the expected increase in quality: the formation levels and grades show lower deviations from the plan (Sturm and Vos 2008). That consequently results in more stability and steadiness in the process chains; key features for making lean processes possible.

The next step from sensor-equipped to connected machines influences the complete process chains and allows an iterative adaption to current conditions. Performed stochastic simulations of dynamic construction machine allocation on construction sites, using the monte-carlo method (Marczyk 1999), are very promising and show improvements of more than 4 % in total working hours and reduction in waiting times up to 80 %. Implementations of the pull principle and Kanban systems in similar use cases, for example the allocation of trucks to a road paver in road construction, achieved a reduction of truck idle times of 86 % and an increased productivity of 66 % (Kaiser and Zikas 2009). Comparing these numbers to the results of the stochastic simulations, the simulations results seem realistic. The already reached improvement rates in the industrial production through the implementation of lean principles give reason to presume that it could even lead to far higher improvement rates.

Not mentioned yet are the costs for implementing the BIM software but regarding Young et al. (2007) a return on investment-rate between 100 and 1000 % is possible. The purchase and use of BIM software is clearly profitable; here it is only being looked at the investments on BIM software regarding the construction machines and their needed performance increase. Taking average prices for modern CAD technology and costs for employee training, small and medium-sized businesses (number of employees 100-499), which take a market share of 44.2 % in the German civil engineering construction market (Federal Statistical Office 2012), are facing costs below 250,000 €. Taking costs given by software producers and the price for modern standard CAD software, a more precise calculation cannot be given so far. In Germany the amortization period for software is 5 years (Federal Ministry of Finance 2005); depending on the fleet, 60,000 € have to be added yearly to the machine costs. In case the constructing company has to create the models itself, the size of the construction machine fleet needs to be estimated. German construction companies have an amortization rate of 2.7 % from their annual turnover (Federal Statistical Office 2010). Divided by the number of companies, there is a yearly depreciation of 755,000 € for each company. It needs to be considered that the depreciation time for machines differs from the software as the excavator described above has an amortization period of 8 years. To show the benefits of the defined system the calculation has been simplified and 25 machines are being used for the described company and machine type, even though the real market varies in amount and type of machines. Interviews show that the interest in BIM technology is mainly driven by the planning team so that in case of system compatibility the executive company will receive the already created model from the planners and only needs to get a proper interface, which means there is no need to buy the full BIM software. Law and payment issues have to be considered handing over and using the model. The following table 3 is depicting a full cost scenario to cover the highest possible financial burden for a company. Combining the results from table 2 and 3 the amount of 1.45 € per hour needs to be added (to the complete system), based on the circumstance that the planning team has got a lack of useful models and the executing company therefore needs to buy the whole BIM software. As a result the hourly machine costs amount to 28.10 € and the desired performance to 52.03 m^3 per hour, which means that, compared to the sensor equipped machines, an efficiency increase of 7.8 % is needed.

That leads to a discrepancy between needed performance increase and simulated performance increase of 3.8 %. A possible explanation for this are the uncertainties regarding the amount of 25 machines used, which seems to be low for a company employing around 300 people. Therefore this is considered a lower bound.

A calculation with 77 machines leads to 0.47 € additional costs per hour instead of 1.45 €, this implicates overall costs of 27.12 € per hour and a needed performance of 50.22 m³/hour. Compared to the sensor equipped machines the needed performance increase is 4 %, which puts the needed performance increase and the costs for the technology to an equal, marking the break-even point.

Table 3: Costs for integrated Software solution

Average turnover company 100-499 employees			27,975,000 €
Average depreciation	2.7 %		755,000 €
Acquisition costs machine			245,500 €
Amount machines		**≈ 25**	
Yearly machine hours		**1381,25**	
Yearly cost of software		**50,000 €**	
Additional Cost per machine hour		**1.45 €**	

The calculations in this paper are only laid out for an excavator as it is often the bottleneck on the construction site. Its work cycle is the most difficult to optimize and control. Mapping the whole process chain of excavator, transportation vehicles and graders or dozers does promise much more potential for optimization, which also indicates that this result counts as a lower bound. Research on a road construction site has shown that by the use of machine sensors the cooperation of dozers and graders gains a performance increase of 101 % (Caterpillar Inc. 2006).

It has not been possible yet to verify the second hypothesis due to missing data, but there are indications to its truthfulness. The increase of performance seems a bit low compared to other Kanban and machine sensor implementations. Also economies of scale should be regarded. This leads to further research questions: Which performance increase can really be achieved? How does a construction site have to be structured or which specific boundary conditions of different types of construction sites promote additionally the use of this system?

CONCLUSION

This paper shows the opportunities of an integrated IT-system to the earthwork construction site. Its use fosters the lean principles in terms of a global view at the construction site, the reduction of waste, in terms of waiting times and needed rework, and a higher level of transparency. The system also allows an easier quantification of the work processes, which enables the implementation of a continuous cycle of improvement.

Using actual figures, the paper demonstrates that the combination of machine sensors, a communication platform and visualization technology promises higher work efficiency and costs for implementing the system can be covered even regarding the most expensive construction machine (sensor to machine cost ratio), the excavator. The already existing increases in productivity for graders and dozers show the necessity for companies to invest in this new technology.

Further research is essential to picture the whole impact of this new approach. Effects like fuel savings, personnel savings or the savings in construction material could not be shown in this paper. It is expected that the productivity will show far more increase if those savings are included as well. Also the overall impact of enabling lean methods needs to be quantified by field tests. First test runs of such a system are conducted in spring 2013.

REFERENCES

Adamu, I. and Howell, G. (2012). "Applying Last Planner in the Nigerian Construction Industry". *Proceedings of the 20th Conference of the International Group for Lean Construction*, San Diego, California, USA, 2012.

Adhalsteinsson, D.H. (2008). "GPS machine guidance in construction equipment", Final Project BSc. University of Reykjavik, Island.

Akinsola, A , Dawood, N. and Hobbs, B. (2000). "Construction planning process improvement using information technology tools".CIB W078 International Conference: Construction Information Technology 2000

Bowden, S., Dorr, A., Thorpe, T., and Anumba, C. (2006). "Mobile ict support for construction process improvement." *Automation in Construction*, 15(5):664-676.

Brynjolfsson, E. and Hitt, L.M. (2003) "Computing Productivity: Firm-Level Evidence". *MIT Sloan Working Paper No. 4210-01*.

Caterpillar Inc. (2006). "Road Construction Production Study".

Central Federation of the German Construction Industry. (2007). "Baugeräteliste 2007" (Technical and Economic Construction Machinery Data), Bauverlag Bv Gmbh, Berlin, Germany.

Eastman, C., Teicholz, P., Sacks, R. and Liston, K. (2008). "BIM handbook: a guide to building information modeling for owners, managers, designers, engineers, and contractors" John Wiley and Sons.

Eckblad, S., Bedrick, J. and Rubel, Z. (2007). "The Possibilites of an Integrated Approach". Presentation to the AIA California Council Change Conference, June 25-26, San Francisco, USA.

Federal Ministry of Finance. (2005). "Bilanzsteuerrechtliche Beurteilung von Aufwendungen zur Einführung eines betriebswirtschaftlichen Softwaresystems (ERP-Software)" (Fiscal assessment of expenses to the introduction of business software systems (ERP-software)), Official letter of the ministry, 17th October 2005, IV B 2, S 2172, 34/05, Germany.

Federal Statistical Office. (2010). "Kostenstruktur der Unternehmen im Baugewerbe" (cost structure of companies in the construction industry), Fachserie 4, Reihe 5.3, Germany.

Federal Statistical Office. (2012). "Tätige Personen und Umsatz der Betriebe im Baugewerbe" (Employed persons and turnovers of companies in the construction industry), Fachserie 4, Reihe 5.1, Germany.

Fernández-Solís, J. L. and Mutis, I. (2009). "The Idealization of an Integrated BIM, Lean, and Green Model (BLG)". In: Underwood, J. and Isikdag, U. "Handbook of Research on Building Information Modeling and Construction Informatics: Concepts and Technologies", pages 302-334.

Girmscheid, G. (2010). "Leistungsermittlungshandbuch für Baumaschinen und Bauprozesse" (Manual for the determination of performance for construction machines and processes). Springer Berlin Heidelberg.

Hamzeh, F.R., Ballard, G. and Tommelein, I.D. (2008). "Improving Construction Work Flow - The Connective Role of Lookahead Planning". *Proceedings*

Sixteenth Annual Conference of the International Group for Lean Construction, IGLC-16, Manchester, United Kingdom, pages 635-646.

Jonasson, S., Dunston, P., Ahmed, K. and Hamilton, J. (2002). "Factors in Productivity and Unit Cost for Advanced Machine Guidance." *Journal of Construction Engineering and Management*, 128(5), 367–374.

Kaiser; J. and Zikas, T. (2009). "Lean Management in Road and Underground Construction". *BauPortal, 121(5)290-293*, May 2009.

Kirchbach, K., Bregenhorn, T. and Gehbauer, F. (2012). "Digital Allocation of Production Factors in Earth Work Construction". *Proceedings of the 20th Conference of the International Group for Lean Construction*, San Diego, California, USA, 2012.

Kirchbach, K. and Runde, C. (2012). "Augmented Reality for Construction Control", *Proceedings of the 16th International Conference on Information Visualization*, Montpellier, France, pages 440-444.

Lostuvali, B., Alves, T.d.C.L and Modrich, R.-W. (2012). "Lean Product Development at Cathedral Hill Hospital Project". *Proceedings of the 20th Conference of the International Group for Lean Construction*, San Diego, California, USA, 2012.

Marczyk, J. (1999). "Principles of Simulation-Based Computer-Aided Engineering". FIM Publications.

Sacks, R., Koskela, L., Dave, B., and Owen, R. (2010). "Interaction of Lean and Building Information Modeling in Construction." *Journal of Construction Engineering and Management*, 136(9), 968–980.

Shin, D. H. und Dunston, P.S. (2008). "Identification of application areas for augmented reality in industrial construction based on technology suitability." *Automation in Construction*, 17(7):882-894.

Stempfhuber, W. (2006). "1D and 3D Systems in Machine Automation", FIG 3rd IAG / 12th FIG Symposium, Baden, Germany.

Sturm, A. and Vos W. (2008). "New Technologies for Telematics and Machine Control-" *Proceedings 1st International Conference on Machine Control & Guidance,* Zurich, Switzerland.

Tezel, A., Koskela, L., and Tzortzopoulos, P. (2009). "Visual management - a general overview", *5th International Conference on Construction in the 21st Century (CITC-V)*, Istanbul, Turkey.

Young, N.W., Jones, S. A., Bernstein, H. M. (2007). "Interoperability in the Construction Industry". SmartMarket Report. McGraw Hill Construction.

Zimina, D., Ballard, G. and Pasquire, C. (2012). "Target value design: using collaboration and a lean approach to reduce construction cost". *Construction Management & Economics*, Taylor and Francis Journals, 30 (5) 383-398