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Innovative Earthworks - Recent Trends in Earthwork Construction

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Abstract

The interest in innovations in earthwork construction is increasing and continues to gain more and more in popularity. Earthwork contractors have begun to think about alternative ways to increase productivity by applying new technologies. In this context they are trying to utilize positioning systems and robotics on their earthmoving machines in order to improve processes and to reduce workforce and total costs at the same time. However, as with many innovations, there exist companies that have not invested in these technologies yet. The objective of this paper is to investigate in innovative technologies and their relating future application-possibilities in the field of earthwork construction. Therefore, this paper conducted an in-depth literature review of relevant innovation topics. Additionally, a survey among earthwork industry experts was conducted in Germany, in order to identify several benefits and challenges of positioning systems and robotics utilized on earthmoving machines.

Rezumat

Interesul pentru inovațiile în construcția de lucrări de terasament crește și continuă să câștige tot mai mult în popularitate. Antreprenorii din domeniul construcțiilor au început să se gândească la modalități alternative de creștere a productivității prin aplicarea noilor tehnologii. În acest context, ei încearcă să utilizeze sisteme de poziționare și robotică pe mașinile de tratare a pământului, pentru a îmbunătăți procesele și pentru a reduce în același timp forța de muncă și costurile totale. Cu toate acestea, ca și în cazul multor inovații, există companii care nu au investit încă în aceste tehnologii. Obiectivul acestei lucrări este de a investiga tehnologiile inovatoare și legătura cu posibilitățile lor viitoare de aplicare în domeniul construcției de lucrări de terasamente. Prin urmare, această lucrare a efectuat o revizuire aprofundată a literaturii de specialitate cu privire la subiectele relevante. În plus, în Germania a fost efectuat un sondaj în rândul experților din industria de terasament, pentru a identifica mai multe avantaje și provocări ale sistemelor de poziționare și robotică utilizate pe mașinile de împrăștiere a pământului.

Keywords: Positioning Systems and Robotics, Innovative Earthworks, Construction Innovation, Machine Guidance, Fleet Management Systems

1. Introduction and motivation

Nowadays, innovation is getting more and more important for companies that strive for growth and try to withstand an increasing competitive pressure. In particular, innovations in the area of automation and digitalization force companies to adapt competences at ever-shorter intervals, simultaneously pressuring them to remain at the heartbeat of tomorrow's industry developments. Digitalization and the interaction of men and machines are currently in the focus of strategic considerations of nearly every future-oriented company. Following this, the digitalization of the entire value chain is of considerable relevance. And especially for construction companies, which in general are regarded to be less innovative and which are characterized by a rather conservative image, the points above are particularly relevant due to the enormous utilization of machines needed for earthworks. These developments will have fundamental effects on both the construction equipment manufacturers as well as the construction companies. This means that the entire industry will be faced with groundbreaking developments, which have to be considered not only with respect to the coordination of business processes, but also with regard to measures referring to the company's internal infrastructure. Although economic research has shown little interest in exploring the construction industry so far, it must by no means to be ignored because of its size and economic relevance. Within the scope of this research paper, innovation is analyzed with respect to earthwork construction, utilizing positioning systems and robotics. Therefore, this paper tries to outline how the use of construction machines, applying those technologies, may contribute to more efficient earthworks over the entire life cycle of earthwork construction projects. Based on these investigations, both an extensive literature review and a questionnaire survey was carried out in order to research innovation regarding the use of groundbreaking technologies in earthworks. The results of this investigation are presented and interpreted in this paper, addressing both the construction industry supplier side, as well as the construction companies as end users.
In this context, this research will examine the following research questions:

RQ1: What are the latest developments of innovations in earthwork construction?
Therefore, an extensive literature review is conducted in order to get an understanding of innovation in terms of earthwork construction. Accordingly, the state-of-the art together with the latest developments are described.

RQ2: What is the current State of Practice regarding innovations in earthwork construction?
This is researched through an analysis of the data won from the questionnaire survey. The purpose is to identify the companies' experiences referring to the technologies described as well as to explore the participant's assessment on the benefits of innovation in general and positioning systems and robotics in particular.

RQ3: What are the future trends?
This is analyzed in bringing together the results from the questionnaire survey with the newest findings in academic literature on positioning systems and robotics applied on earthmoving machines.

2. Methodology

First, an extensive literature research was conducted, using Google Scholar and several databases such as ASCE, EMERALD and ASCE, in order to determine the latest developments of innovations in the field of earthwork construction. Therefore, search keywords like earthwork construction, earthmoving machines, earthmoving equipment, machine guidance systems, innovations, productivity, and optimization were involved in the articles searched. Where it was considered meaningful for reasons of plausibility some additional papers were included in the research. After collecting the latest academic contributions, an analysis was performed in order to classify the main areas of interest and to answer the first research question. It is acknowledged that the review focuses on innovations in earthwork construction, having a closer look on innovative technologies applied on earthmoving machines in a narrower sense.

In addition to the literature review, a questionnaire survey was applied, in order to research the current State of Practice regarding Earthmoving Machine Automation. The survey should provide further insights regarding the companies' experiences on the technologies described. Therefore, several questions were outworked to experience the participant's assessment on the benefits of innovation in general and positioning systems and robotics in particular.

In a final step, the results from the literature review and the survey were brought together and synthesized, in order to determine the future trends regarding innovative earthmoving machines. The aim is to predict future developments and to provide a direction for future research.

3. Literature Review

3.1 Innovation in Earthwork Construction

With regard to construction companies, innovation research seems to be still in its embryonic stage. In general, management theory is not really interested in researching construction, but more focused on the glamorous high-tech industries. Although some contributions in academic literature were treating innovation in construction, there are four authors standing out [1], [2], [3], [4], [5]. However, preliminary researches have failed to establish a standard definition for construction innovation and thus creating confusion so far [6], [7]. More particularly, there seems to be a dearth of research investigating in innovation from the perspective of a small or medium sized construction company [7]. It's important to state that innovation for a small earthwork contractor means something different than for a multinational construction company. Because the construction sector is very diverse, there is not a single way in which innovation occurs. Moreover, construction is partly manufacturing (materials, components, equipment) and partly services (engineering, design, surveying, consulting, and management) industry [8]. So, a variety of definitions for construction innovation can be found within the academic literature, as shown in Table 1.
Innovation in this research is defined as the actual use of non-trivial change and improvement in a process, product, or system that is novel to the institution and generates practical or commercial benefits. Following this definition, innovation in earthwork construction in a narrower sense describes the concept of innovation in view of an earthwork contractor. As a consequence thereof, an innovation in earthwork construction may be a new construction method or technique, generating monetary or practical benefits, as a possible implication of applying new construction machines and/or materials within the firms' construction processes [9].

3.2 Innovations in Earthmoving Equipment and its Flow into Construction

Manufacturers and suppliers in particular are key drivers of technological innovation in construction, providing a wide range of heavy machinery for earthmoving operations [10]. Earthmoving machines are a part of the construction equipment industry including for example dozers, hydraulic excavators, scrapers, and graders. Throughout this paper the term "earthmoving machines" is used to explain these kinds of equipment.

By tendency, manufacturers invest far more in research and development than contractors do and, subsequently, are more likely to develop product and process innovations [11], [12]. In this context, contractors usually implement product innovations developed by manufacturers in order to improve their earthwork process performance. From the perspective and level of the contractor, this in turn often yields in a process innovation on an earthwork site. In other words, the construction equipment industry feeds the construction industry innovation and, thus often, is the originator of process innovations implemented in the latter.

Based on agricultural tractors in the early 1900s a variety of entire new heavy earthmoving machines were introduced to the construction market und further developed since then. Haycraft (2002) described major technical advancements regarding earthmoving equipment from the beginning of the agricultural industry to the present [13]. The history of product development and evolution of earthmoving machines was also researched by Haddock 141]. Moreover, Cohrs investigated specific technical advances of several equipment types from the very early use of machines for earthmoving [15]. Furthermore, an overview about the most important machinery types for heavy earthmoving today can be found in the Caterpillar Performance Handbook [16]. In this context, several researchers have analyzed the effectiveness of manufacturers' innovations concerning heavy machinery. Thereby the focus is on the contractor as end user and its on-site performance improvements with changes in construction productivity and costs [10], [17], [18]. Incremental improvements in the machine form could make the earthmoving equipment more productive, versatile or simple. Referring to that, one can speak about innovations that occur either through a new synthesis of available technologies or a new technology for a system.

The focus of the following survey is on innovation regarding heavy earthmoving machines and its application on earthwork sites. Thereby the subject of special interest is particularly on innovative control and information systems (positioning systems and robotics) with tremendous potential for process innovations by integrating machines with civil designs to improve overall earthwork site operations [10].

3.3 Conventional Earthworks vs. Innovative Earthworks

Traditional earthwork procedures are highly dependent on the skills and experience of on-site managers, equipment operators and surveyors. Thereby the conventional system requires surveyors to stake and re-stake, check the resulting surface, and particularly calculate the volumes of moved earth [19]. Surveying has to be executed periodically in tight correspondence to the work progress. First of all, designs are developed using a survey of the construction site. Traditionally, these designs are transferred to the field by placing survey stakes at the key locations, whereby the number of stakes depends on the complexity of the design. In other words, the surface contours of embankments and slopes etc. are visualized by the machine operator by means of profile templates or stakes [20]. The cut and fill measurements are marked in the meantime with earthworks going around them. However, it is important to take into account that it is nearly impossible to supply enough survey stakes to model the original design with the same resolution described in the site plans. The stakes provide the only visual guidance for designed elevation of any particular point or region [21]. Because these stakes are the only source of information for the equipment operator concerning the surface, it is difficult for him to correctly adjust the position of the cutting edge (bucket, blade etc.) at every location he works and model the envisaged design with high accuracy. This construction process, more importantly, requires an additional site worker to support the operator, while work is restricted to daylight times. As the job progresses, the surveyor has not only to do additional surveys to convey information on the next construction phase, he usually also has to make changes to the current work and document the completed work against plan. Moreover, he has to reset stakes that have been knocked down during site operations. Because operators have to hold on the operation, while the surveyor rechecks the grades, significant delays may arise. Another problem emerges, if the operator is continuing operation without any resetting of the stakes because the surveyor is not on site. This may cause serious deviations from the desired design surface with the consequence of expensive reworks [19]. Following this, the surveyor has to provide a strong interface between the engineering design and the machine operator onsite. Surveyor, operator and site worker have to work closely together to produce a high quality final result. Each participant has his own information with no digital platform to share it in real time. This conventional earthwork process is labor intensive, time consuming and contains high potential for fatal errors. Rework caused by these errors is always expensive and thus unproductive.

The return on invest is usually the crucial measure for the construction industry when investing in innovative construction technologies. Today's earthwork contractors have not only to perform all parts of a job more accurately than ever before, they were also confronted with tight project schedules and budgets, which means doing the jobs more faster and cheaper, while still maintaining profitability [22]. Earthwork construction is a branch with close tolerances, where precision, accuracy and data management can make or break the bottom line. Processes on an earthwork job site resemble an industrial manufacturing process and thus have to be managed adequately with appropriate innovative tools [23]. While the concept of a digital factory has already been successfully implemented in the automotive and manufacturing industry, earthwork contractors are still searching for new ways to adopt and implement innovations that follow digital principles [24]. The challenge is to identify innovative solutions that provide a high level of process and workflow integration from the early design phase to the finished project, delivering significant improvements in productivity throughout the whole construction's lifecycle [22]. One promising innovative approach therefore is the utilization of positioning systems and information technology. As Figure 2 shows, a combination allows a cross-linking of construction machines and thus offers a high level of information transparency among all project participants [24].

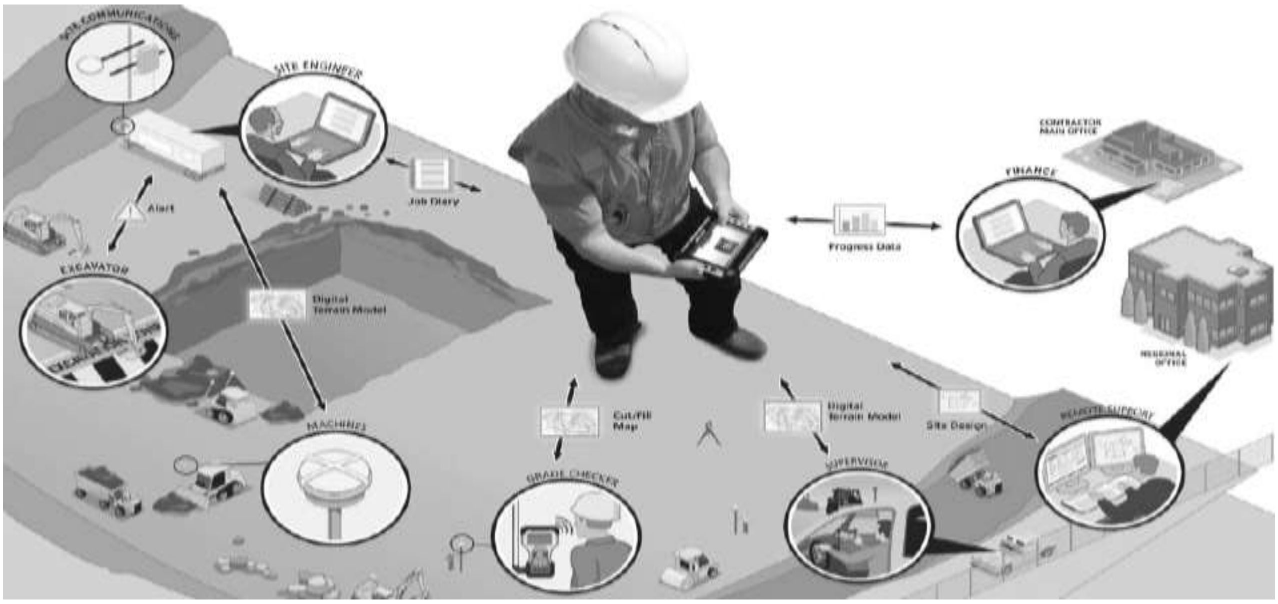

Figure 2: Combination of Positioning Systems and Information Technology in Construction
Source: [25]

The collected and shared information ensures an improved coordination with reduced waiting and unproductive times. Advanced earthmoving systems using GPS provide, for example, a basic concept of a dozer or motor grader to grade without any stakes [19].

3.4 Work Process of a Digital Earthwork System (CAM)

A machine control system together with automated production control can be referred as CAM on earthwork construction jobsites [26]. For the work process of a CAM earthwork system firstly a 3D model of the earthwork site has to be constructed. After that, a CAD production model is designed and superimposed to the DTM, before the data is exported in a proprietary file format and transferred to the machine's control box via USB or Internet. Furthermore, the geometric model has to be positioned in the site coordinate system, in order to use the data for controlling measurements and construction machines [27]. Afterwards, a coordinate transformation file is generated and transferred to the deployed devices. Following this, a considerable amount of planning, surveying and design is necessary before an earthmoving machine can be deployed with an automatic machine control system on site. Therefore, civil engineers, surveyors and designers need powerful design and CAD packages, such as Autodesk, Inroads or Geopak [22]. Once the design data is completed and transferred onto the machine's control system and onto the engineer's site controllers, one could speak about an integrated construction site, where holistic information about the project is available to all project participants digitally. While the GNSS receiver or robotic total station on the machine computes the blade's or bucket's exact position, the control box determines the exact position of the machine's working tool. Accordingly, the system incorporates RTK GPS data with design information. The cut and fill information which is based on the current elevation and design is displayed on the graphical user interface in the cabin, showing exactly where the machine is on site and where the working tool is relative to the production plan no matter whether it is dark or dusty. Because new grade or pad elevation can be set right in the cabin, the operator has not longer to wait for grade stakes to be set or repositioned. Thus, on-field changes can be made very quickly, and the operator always knows exactly where grade is [22]. The main challenge in this context is to have control about the 3D data flow from design to construction. This is especially important on big construction sites with many project participants and sub-contractors working with different machines, systems and data files [27]. With respect to this, an online connection between the CAD application and the machine's control box is essential. Such an online connection between the office and on-site machines facilitates fast data exchange of updated production models and on phone support via remote desktop. This imposes additional requirements, while opening new valuable possibilities at the same time. The combination of sensors and information technology allows a cross-linking of earthwork machines and thus offers a higher level of information transparency for all project participants. This higher transparency not only leads to a higher productivity of the machine, but also to a more effective process chain [24].

4. Questionnaire Survey on Innovation in Earthwork Construction

In order to provide answers to RQ2 - *What is the current State of Practice regarding innovations in earthwork construction?* - a questionnaire survey was conducted among earthwork industry experts. Subsequently, the results of the questionnaire are presented, trying to present insights to innovative earthworks applying positioning systems and robotics. Depending on the perceptions of industry experts, a base of knowledge about positioning systems and robotics is developed, outlining the state-of-practice, future trends and opportunities of innovations in heavy earthwork construction. The findings presented also demonstrate the potential for a further investigation concerning innovations in earthwork construction and thus should hopefully motivate future researchers to attempt studies and conduct more research in this field. The questionnaire included both close-ended questions with predominantly ranking scale response options, as well as open-ended questions. Concerning the ranking scale questions, the participants' assessment was conducted with answers on a 5-point Likert-Scale that reflect the subjects' agreement with the questions by five degrees [28]. Following that, the data is analyzed depending on the type of data and with respect to the research theme.

Response Rate:
The research response rate of a mailed questionnaire is the number of questionnaires returned. It is typically expressed as a percentage of the number of subjects contacted and invited to participate. In this paper a total number of 300 questionnaires were sent out to construction professionals in Germany.

Table 1: Response Rate

Condition	Amount
E-Mails/ Questionnaires sent	300
Totals responses	77
Invalid questionnaires	12
Valid questionnaires	65
Percentage of valid questionnaires	21,67%

Demographic Profile of Respondents:
To make sure, that all participants have major experiences with earthwork construction, the first questions provide answers to their field of activity. Additionally, it was asked for the company's gross annual revenue and the number of employees, in order to identify potential coherences of innovation activity and company size. As Figure 3 shows, the majority of respondents (80,4%) are construction contractors, while the remainder companies are mainly consultants, surveyors and developers.

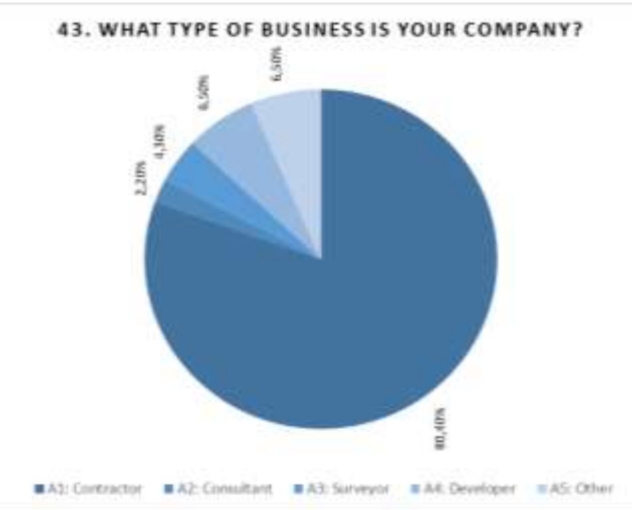

Figure 3: Question 43 – Business Type

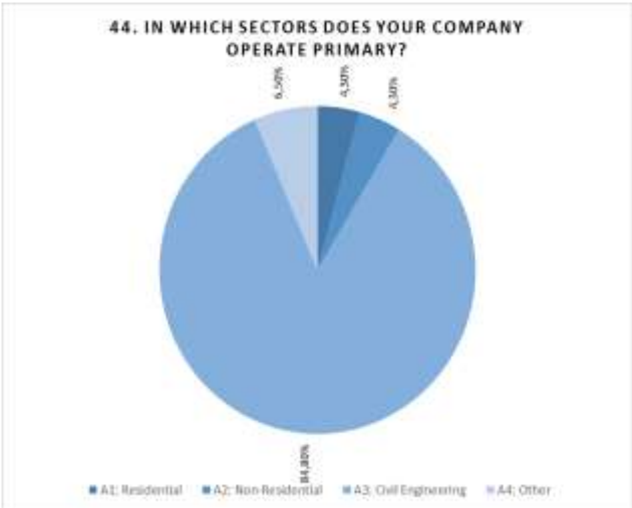

Figure 4: Question 44 – Sectors of Operation

Respondents were also asked in which sector the company that they are currently working for, primarily operates. This question was conducted so it could be possible to make a comparison of answers from the participants across sectors, if necessary. According to Figure 4, a total of 84,8% of respondents' companies is working in civil engineering construction. Because the theme of this paper is particularly focused on earthwork construction, there is a special interest to gain insights not only on the business type but also on the share of earthworks of every company. Therefore, all participants were asked how they assess the share of earthworks in relation to their company's gross annual revenue. According to Figure 5 only 6,7% of the respondents' companies have no revenues on earthworks, whilst the majority (64,7%) generates more than 25% of annual revenues solely with earthworks. Moreover, 93,4% of companies are acting in earthwork construction. This concludes that the majority of respondents not only have significant experiences in construction, but also especially in the field of earthwork construction. Figure 6 shows that 63,0% of companies generate annual revenues of less than 50 Million Euros. In addition to that 67,4% of companies employ less than 250 workers. Following that, and according to the definition in the EU recommendation 2003/361, the majority of companies in this study can be defined as SMEs.

Market Conditions:

Regarding the competitive environment in Earthwork Construction, more than 95% of companies are aware of high pricing pressure and competitiveness whereas the strongest competitive factors are perceived to be price and productivity. Hence, this could be a reason that 84,6% of respondents stated that their company always searches for new production technologies and 69,2% of companies are steadily searching for new sales markets. Aside from that, more than 75% of respondents believe that the most important levers to enhance competitiveness and successfully face competition, is the support of innovation and the deployment of newest technologies. This substantiates the fact that increasing productivity is perceived to be the most successful competitive strategy for construction companies doing heavy earthworks.

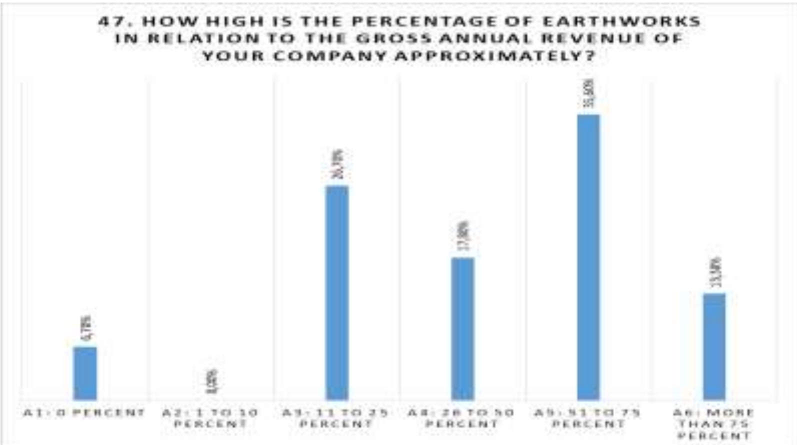

Figure 5: Question 47 – Share of Earthworks

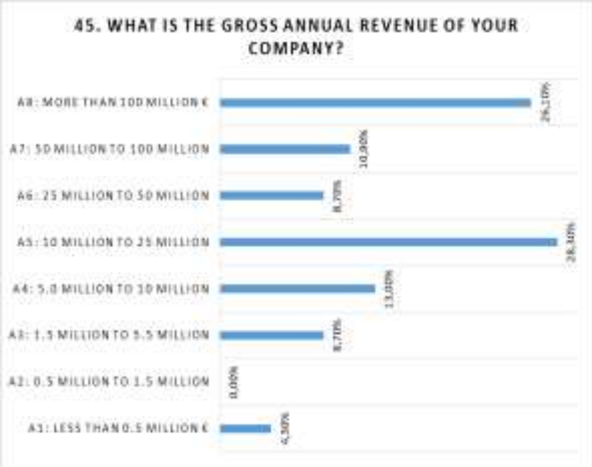

Figure 6: Question 45 – Company's Gross Annual Revenue

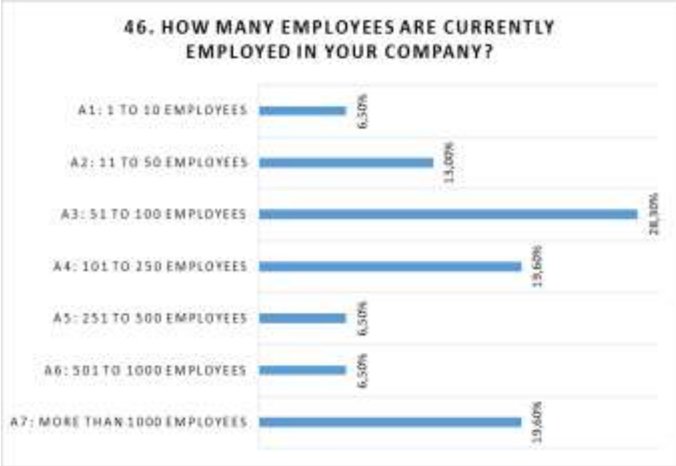

Figure 7: Question 46 – Company's Employees

Innovation Activity:

Concerning the innovation activity, the preceding findings are consistent with the belief of the respondents that a high degree of innovation particularly leads to increased profitability, increased productivity, optimization of processes and thus improved competitiveness. At that, the respondents suggest that a high degree of innovation most probably affects the productivity positively. Even though, the value of innovation is believed to be a cardinal issue in terms of productivity, 70,9% think that earthwork contractors are less innovative compared to manufacturing firms. All the more it is surprising that 67% of companies have no responsible person for innovation management. In fact, innovation seems to be solely a part of top management as a kind of side job to their literal responsibilities. Accordingly, most respondents answered they would rather have management people look for innovative techniques to improve earthwork processes than their employees, although working with the machines is their daily business.

Machine Guidance Systems as Process Innovations in Earthmoving Operations:

The majority 85,5% of companies already use machine guidance systems on heavy earthmoving machines. In this context, Figure 8 shows that most respondents already have experiences with 2D and 3D machine guidance systems. And as Figure 9 illustrates, they also have deployed systems on different earthmoving machines. Thus, most respondents (73,5% - 85,7%) are already familiar with control systems on motor graders, tracked excavators and dozers. But Figure 8 also shows that there are several machines, which were instantaneously not considered to be equipped with guidance systems.

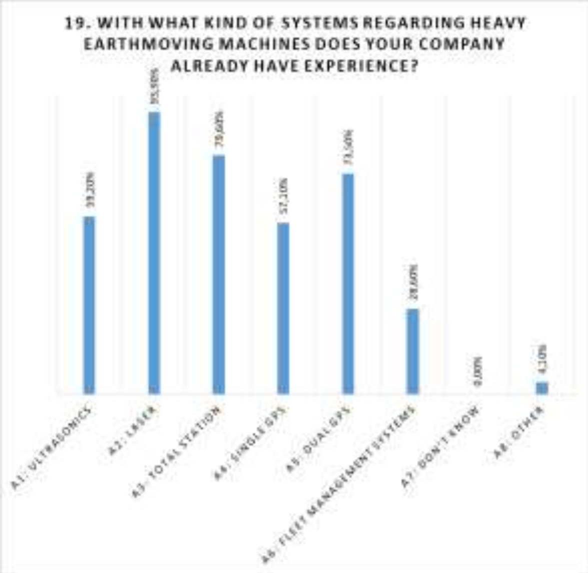

Figure 8: Question 19 – Experiences with Machine Guidance Systems

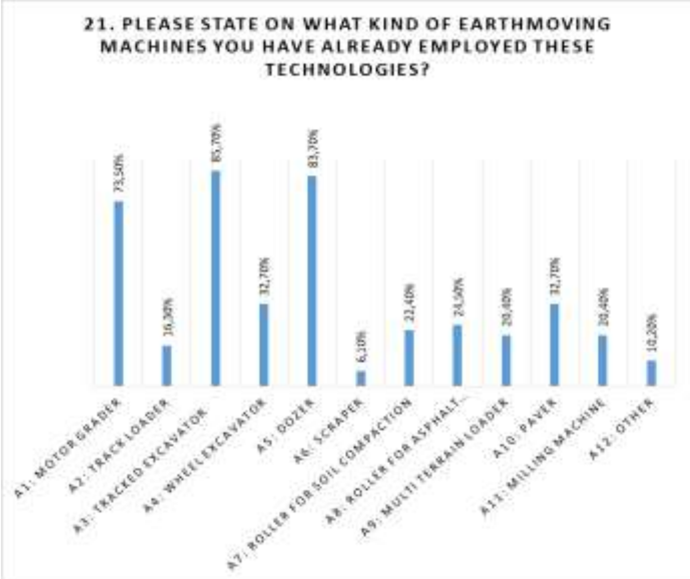

Figure 9: Question 21 – Deployed Earthmoving Machines

Notably, 79,2% of companies already have more than 3 years of experience with these systems with several company departments being involved. Besides on-site construction and surveying, design, disposition and maintenance are partly integrated.

The use of Machine Guidance and Fleet Management Systems:
Concerning the benefits of automation and robotics, the respondents estimate that the deployment of machine guidance systems will lead to increasing productivity, optimization of processes, and increasing quality. Thereby they consider an increasing productivity to be the most probable added value. In view of the industry experts, machine guidance systems will unfold the most added values when deployed during grading operations, excavation work, slopes and terrain modeling. Additionally, and in view of most respondents, a fleet management system may be most valuable to examine asset utilization and to dispose machinery. In combination, the majority of respondents (65,4%) estimate the potential for savings to be 20% or higher when using machine guidance systems and fleet management systems on typical earthwork sites. Hence, the systems seem to be best suited to civil engineering projects with huge proportions of earthworks.
Moreover, the experts believe that the systems will have positive impacts on key performance indicators of earthwork construction. In consequence, they predominantly assessed that not only the output of operational hours will be increased, but also that the process’s costs and labor utilization will be reduced.

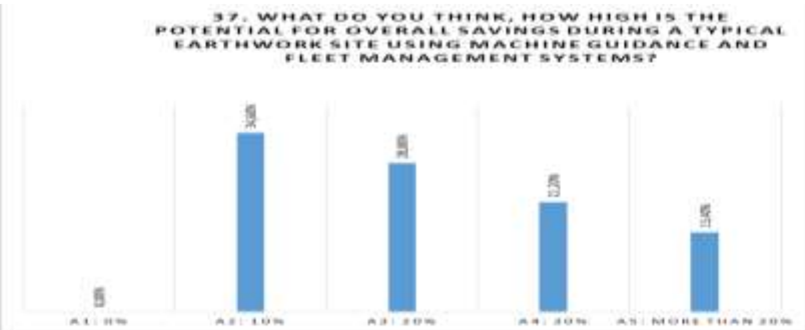

Figure 9: Question 37 – Estimated Savings

Future Trends and Opportunities:
The estimated future trends regarding automation and robotics in earthworks are quite diverse, ranging from significant larger fields of application through to the cheaper systems. The majority also believes that the number of earthwork companies using machine guidance and fleet management systems will increase significantly enabling the firms to operate more efficiently. Moreover, 61,5% agree or strongly agree that both systems will affect nearly all departments of a construction company in the future because of the necessary information those systems generate. But it is also worth mentioning that more than 40% of respondents don't believe in autonomous and remote controlled earthmoving machines in the upcoming 10 years.

5. Conclusions and Future Research Directions

This research described the latest developments of innovations in earthwork construction and thus builds a base of knowledge for practioneers. Accordingly, the current state-of-the art together with the latest developments were described. In this context, new enabled work procedures and changed possibilities regarding the utilization of different systems on different earthmoving machines in the course of different earthmoving operations were discussed.

Additionally the current State of Practice was researched through an analysis of the data won from the questionnaire survey. The companies' experiences referring to the technologies described were identified an discussed. Furthermore, the participant's assessment on the benefits of innovation in general and positioning systems and robotics in particular were explored. The survey has shown that innovations are of serious importance for practioneers in order to face current market conditions and in particular to counter increased cost pressure and competition. The respondents consider that innovation is an essential prerequisite for increasing productivity. This is of peculiar interest, since an increase in productivity is classified as the most appropriate strategy to combat competition.

While literature revealed that machine guidance systems provide a high potential for productivity improvements on earthwork sites, the survey validates that the majority of respondents attest to those systems an increasing importance, estimating that utilization will increase significantly in the future. It is very likely that utilization will increase in the near-term and thus will become an industry standard in earthwork construction. Although the majority of respondents currently may not believe in autonomous construction machines in the near future, literature shows that the latest academic research is concentrating on exactly this topic. The research results reveal also that due to the technical progress and the high acceptance of these systems it can be expected that a deeper integration into the existing company IT landscape will take place in the future. This means that the earthwork construction site of tomorrow will certainly be networked and connected with all affected internal company departments. As a result, the future's main emphasis should be placed on the compatibility-creation of different systems in order to allow all project participants to simultaneously monitor the construction and productivity progress through specifically developed online portals.

It should be noted that digitization and automation in earthwork construction is currently in its infancy and new advances in IT and sensor technology will soon offer completely new fields of application with deeper integration possibilities. Following this, future research efforts should focus on digitization strategies for earthwork contractors. In particular, the Internet of Things, Smart

Sensors, Earthwork BIM, Visualization and Virtual Reality will be topics of interest. Connected devices and products will offer completely new possibilities for earthwork contractors from predictive maintenance to new services and new business models.

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