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A Thematic Review of Main Researches on Construction Equipment over the Recent Years

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Abstract

A considerable body of literature has been dedicated to research studies on construction equipment. Many topics have been discussed and analyzed with various conclusions being reported. However, research papers published in relation to construction equipment, are highly diversified and there is a lack of systematic analysis and classification. Hence, a complete understanding of the topic is not possible, nor is the assessment of any future research direction. A meta-analysis of the latest journal papers dedicated to construction machinery would not only delineate the different fields the academic research has been concentrated on, but it would additionally reveal potential gaps for future research.

In the current study, through a systematic review of the academic literature that has been published over the last decade primarily identified via online databases, main research themes such as optimization, maintenance/downtime, productivity, robotics and automation, operator's competence, innovation and environment are defined and discussed and future research directions are proffered. The outcome of this paper will facilitate future researchers to develop an appreciation of the progress on construction equipment and its potential functions and provide future research directions on this field.

Keywords: construction equipment; optimization; productivity; maintenance; research

1. Introduction

"Construction equipment" (CE) or "Heavy equipment" refers to heavy-duty self-propelled vehicles, specially designed for executing construction tasks. Its use has a significant importance in the successful realization of civil projects; it therefore represents a major capital investment for the construction industry. In this research, the term CE refers to the machinery that is used especially for earth-moving operations. Those earthworks mainly consist of four basic processes: excavating, hauling, spreading, and compacting [1]. Typical earthworks are building foundation work, road construction, dam construction, airport construction and strip-mining. Depending on their kind and size the earth-moving operations are carried out by single machines working independently or by sets of machines working together and consist of excavators, dump trucks, loaders, compaction rollers, graders, scrapers, etc.

There is a lot of research work on CE. However, research papers published in relation to CE, are highly diversified and there is a lack of systematic analysis and classification. Hence, a complete understanding of the topic is not possible, nor is the assessment of any future research direction. This mate-analysis of the latest journal papers dedicated to CE would not only delineate the different fields the academic research has been concentrated on, but would reveal also the potential gaps for future research. A previous holistic research on this subject can only be traced in the review conducted by Edwards and Holt [2]. In their work, the authors highlighted the following points as research directions for the future:

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- Machine maintenance might develop with more sophisticated predictive models that enable "just-in-time" component replacement,
- Concerning the application of the global system for mobile communications facilities, it emerged that there is scope for future research, since plant location and spatial data might be expanded to embrace large fleet management,
- The concepts of autonomous machine control, automated systems and robotics might all be more attractive to researchers in the future given the advantages of "unmanned" machines, a matter which is also related to aspects of safer working conditions.
- The adoption of nanotechnology and the production of hybrids are potential routes of development,
- There is a need to enhance research sharing between the industry and the academic community.

Given the above, an updated review on the latest published academic papers dedicated to construction machinery would not only indicate the fields the research was eventually directed to, but it would additionally reveal any potential gaps for future research. The paper begins by presenting the method employed to determine the major research outcomes, followed by a review of the academic papers. Principal research themes are identified; practices and possible gaps in research are discussed and future research directions are proffered. Finally, conclusions are drawn.

2. Methodology

A search (2016) via online databases such as SCOPUS, ASCE, ELSEVIER and EMERALD was carried out to determine the major research themes related to the field that have been published over the last decade. Search keywords like construction equipment, productivity, optimization, research, earthmoving operations, were involved in the title, abstract or keywords of the articles searched.

Editorials, book reviews, articles in press, conference/seminar reports, discussions and articles published more than a decade ago were excluded from this research. Nevertheless, where it was considered necessary for reasons of documentation, some extra papers were added. After collecting the published work, an analysis was performed in order to classify the main areas of interest. It must be clarified that the sample was indexed in a subjective manner and that some themes might present a lot of commonalities due to the complex interrelationships between them. For example, "*Optimization*" and "*Productivity*" present commonalities as the best fleet selection is determined by productivity constraints of each CE. Moreover, it is acknowledged that the review is in no case exhaustive. The themes and number of papers falling therein are shown in Table 1:

Themes identified	Number of papers detected
Optimization	12
Maintenance/ Downtime	11
Productivity	12
Operator's competence / Health & Safety	11
Robotics/ Automation	9
Innovation	10
Environment	8
Sum	73

Table 1: Number of papers falling within the seven Themes identified

3. Literature review

3.1. Optimization

Optimization deals with finding optimal decisions under the given constraints considering the number of possible alternatives. This theme covers a variety of subjects that involve decision-making to increase resource efficiency of use, minimize construction cost, reduce construction time and improve quality. Construction project scheduling has received a considerable amount of attention over the last years. Many models were developed to assist contractors in optimizing planning of earthmoving operations. For example Moselhi and Alshibani [3], developed a model that utilizes genetic algorithm, linear programming, and geographic information systems (GIS) to support management functions. As such, Zhou et al. [4] presented a review of the methods and algorithms that have been developed to examine the area of construction schedule optimization. The developed algorithms for solving this problem were classified into three methods: mathematical, heuristic and metaheuristic. Appropriate

fleet selection is a prominent issue, attracting strong research interest. Zhang [5] proposed an integrated framework for multi-objective simulation-optimization determining optimal equipment configurations of earthmoving operations; Hola and Schabowicz [6] presented a methodology for selecting an optimum set of collaborating earthmoving machines with the criterion of the minimum time needed or the minimum cost of carrying out the earthworks. Jrade et al. [7] introduced a model with the aim to enable the selection of the optimum equipment fleet based on simple economical operation analysis. Contractors have also started to acknowledge and use the telematics technology as a reliable solution for timely collection of their equipment fleet data. This sub-theme has attracted a particular interest amongst researchers. For instance: Said et al.[8] presented novel methodologies to support heavy equipment fleet managers in using telematics data into two major tasks: fleet use assessment and equipment health monitoring; Alshibani and Moselhi [9] developed an optimization simulation model that uses Global Positioning System (GPS) for fleet selection for earthmoving operations; Akhavian and Behzadan [10] presented a remote tracking technique developed to capture real-time field data from construction equipment to predict the future performance of a construction system in addition to monitoring if all pieces of equipment are operating according to the plan; Pradhananga and Teizer [11] presented the use of low-cost easy-to-install GPS data logging technology for tracking and analyzing construction equipment operation. Overall, construction equipment management can improve construction project performance and contractor corporate performance. Samee and Pongpeng [12] not only studied these relationships by collecting contractors' opinions, but also examined the causal relationships between the construction equipment selection factors and the competitive advantage of contractors [13]. Moreover, Aziz et al. [14] presented a smart optimization model, which incorporates the basic concepts of Critical Path Method with a multi-objective Genetic Algorithm in order to support the balance between time, cost and quality simultaneously for mega construction projects. Finally, Shawki et al. [15] displayed a tool for simulating earthwork operations in most applications of construction.

3.2. Maintenance/Downtime

Maintenance plays a key role in reducing cost, minimizing equipment downtime, improving quality, increasing productivity and providing reliable equipment and as a result achieving organizational goals and objectives [16]. Construction equipment performs to its optimum level if it is maintained properly. Downtime resulting from machine breakdown during operations is one of the most unanticipated factors that have a substantial impact on equipment productivity and organizational performance as a whole [17]. To overcome downtime problems, contractors need to understand the dynamics of downtime as well as its influential factors, and thus manage their equipment as a dynamic process rather than one that is static [18]. In order to be effective, predictive maintenance strategy integrates machine data, prognostics, and remote diagnostic tools, which are critical to increasing machinery uptime. Approaches such as condition-based maintenance are being implemented to deal with the situation. Sensors are applied to detect changes in equipment components. With these solutions, contactors gain insight into operations to understand machinery's health and avoid downtime and excessive maintenance costs. Chen et al. [19] developed a distributed condition monitoring and fault diagnosis system for the hydraulic system of large complex construction machinery, taking into account that more than 50% of the faults of construction machinery is related to its hydraulic system. Equipment health-monitoring is a proactive maintenance tool to estimate the equipment's failure probability, and hence, Said et al. [8] developed a telematics-based equipment health-monitoring framework for collecting vital equipment performance parameters to continuously assess the condition of the equipment and detect signs of possible failure. Some researchers touched upon the factors and parameters that influence the deterioration process and the forthcoming downtime. For instance, Prasertrungruang and Hadikusumo [20] proposed a model that intends to facilitate a better understanding of the relationships among acquisition condition, operational practice, maintenance quality, disposal practice, and downtime consequences of heavy equipment; and Marinelli et al. [21] investigated the impact of various parameters (capacity, age, kilometers, maintenance) on the deterioration process of earthmoving wheel trucks using the statistical method of discriminant analysis. According to this method, any truck can be assigned to a specific condition level, depending on its parameters' values. This allows the effective planning of maintenance activities and the prediction of the consequences that are expected to occur due to the equipment's deterioration including downtime. Similarly, Marinelli et al. [22] presented an Artificial Neural Network (ANN)-based model for the prediction of earthmoving trucks' condition level using the aforementioned parameters as predictors. The model identified an exclusive connection of the condition level with the kilometers travelled and the maintenance level as the impact of the age and capacity was found to be negligible. Mohideen et al. [23] introduced a model that tackles unpredictable breakdowns in the construction plant and thus minimizes the breakdown time. The proposed model enables a quick recovery of the construction plant, according to the breakdown parameters derived from the previous history of the work records/environment. Mohideen and Ramachandran [24] proposed a breakdown code management to provide a focused and unambiguous approach to the maintenance crew to handle any kind of breakdowns in construction equipment. Additionally, Yip et al. [25] presented a comparative study on the applications of general

regression neural network (GRNN) models and conventional Box–Jenkins time series models to predict the maintenance cost of construction equipment; and Curcuru et al. [26] proposed a methodology that minimizes the maintenance cost by determining the time at which the decision must be taken and the starting date of the maintenance process.

3.3. Productivity

The expected work output per time unit (hour or day), usually termed productivity, determines the cost and the duration of construction activities [27] and has consequently achieved much attention in literature. Panas and Pantouvakis [28] in their review research regarding construction productivity explored the different perspectives for measuring or estimating it; while Yi and Chan [29] conducted a systematic review of labor productivity in the construction industry to investigate the state of the art and trends in construction labor productivity. Concerning construction equipment, productivity estimation is heavily affected by the type of operational coefficients and the estimation methodologies taken into account. Based on this, Panas and Pantouvakis [30] proposed a structured framework for comparing different productivity estimation methodologies and evaluating their sensitivity with operational coefficients variation for excavation operations. Rashidi et al. [31] proposed a generalized linear mixed model to estimate the productivity of a common type of bulldozers and compared the outputs with the results obtained by using a standard linear regression model. It was proven that a significant increase in the accuracy and a remarkable reduction in the data variance can be achieved by using the proposed model. Telematics were also used for estimating productivity in near real time. For example, Montaser et al. [32] presented an automated method that utilizes GPS and Google Earth to extract the data needed to perform the estimation process; Montaser and Moselhi [33] demonstrated an automated system that integrates GPS and GIS in a web-based platform used for estimating, monitoring and forecasting productivity of hauling trucks in earthmoving works. Other researches in the field include those by Schabowicz and Hoła [34,35] who applied ANNs not only to predict productivity, but also to predict earthmoving machinery effectiveness ratios; by Marinelli and Lambropoulos [36] who proposed a new algorithmic method for scraper load-time optimization that achieves an improved modeling of scraper earthmoving operations and contributes toward a more efficient cost management and by Oh et al. [37] who developed a driver model for the wheel loader V-cycle working pattern and a 3D dynamic simulation model to analyze working performance and energy flow in each component of the wheel loader. Finally, the work of Rustom and Yahia [38] employed the use of simulation as an effective planning technique for estimating production rates in construction projects.

3.4. Operator's competence / Health and Safety

Operator's competence is the operator's ability to effectively and efficiently apply the machine to the work task. Operator's competence embraces not only aspects of productivity, but also health and safety (H&S) aspects. Regarding productivity, it is acknowledged that operator competence and operator motivation are two entirely different concepts, since a very competent operator can also be demotivated or simply idle. Holt and Edwards [39] in their work identified the superlative role of operator competence in relation to other productivity variables and presented a conceptual approach to overcoming subjective factors when estimating productivity. Concerning H&S aspects, training is widely considered to be one of the best approaches to the accident prevention. Operator training simulators are a key component of such initiatives to serve the purpose of keeping plants operating safely, with optimal performance and reliability. Simulated environments provide safe, controllable conditions in which operators can practice necessary skills such as critical thinking and decision making. The benefits of simulation training have potentially much to offer to the construction training industry particularly in the education and development of entrant level plant operators [40]. Guo et al. [41] suggested the use of game technologies to improve the safety of construction plant works. The game technology-based safety training method provides trainees with an easily operated multi-user virtual environment that allows them to try and study different methods of operating the plant, while helping them identify potential safety problems.

The inevitable coexistence of machinery and ground floor workers results in many work accidents on sites. According to Mc Cann [42] backhoes and trucks were involved in half the deaths with rollovers being the main cause of death of heavy equipment operators. In an attempt to alleviate fatalities and injuries in construction industry many researchers have focused on H&S aspects. Hinze and Teizer [43] in their paper highlighted that blind spots; obstructions and lighting conditions were the most common factors contributing to vision related fatalities. Given the above, Teizer et al. [44] developed a novel blind spot measurement to help identify the blind spots of equipment, to quantify and protect the required safety zone(s); Moreover, Marks et al. [45] presented a technique based on laser scanning for measuring blind spots of four different skid steer loaders and suggested that similar measurement data for several pieces of equipment can be used to provide design suggestions in the future. Teizer et al. [46] also applied a real-time proactive Radio Frequency warning and alert technology to improve construction safety by warning or alerting workers-on-foot and operators in a proactive real-time mode

once equipment gets too close in proximity to unknown or other equipment. Similarly, Marks and Teizer [47] presented a test method to evaluate the capability of proximity detection and alert systems to provide alerts when heavy construction equipment and workers are too close to each other. The use of 3D visualization not only assists equipment control, but also improves operation efficiency and safety, and therefore Gai et al. [48] introduced a real-time visualization method to simultaneously assist heavy equipment operators to perceive 3D working environments at dynamic construction sites. However, Su et al. [49] warned that additional spatial information to the operator may increase mental workload, introduce difficulties in processing the information and consequently may cause malfunction and accidents.

3.5. Robotics/Automation

The use of robotics and automation (R&A) technology becomes essential to construction project success and creates possibilities for the construction company to realize a competitive advantage [50, 51]. A popular subtheme here is "unmanned construction", i.e., work performed by remotely operated construction machinery that corresponds to an operator controlled robot. In environments with great exposure in hard conditions, remote machine operation is the preferred and most efficient solution for the operation of construction machines. Sasaki and Kawashima [52] in their work developed a remote control system for a backhoe with a pneumatic robot system, while Kim et al. [53] developed an excavator teleoperation system with movements of a human arm.

Furthermore, towards facilitating the use of automated construction equipment, Seo et al. [54] presented an excavation task planner devised to incorporate the intelligence of a construction planner and a skillful operator into the robotic control mechanism of an automated excavation system; Son and Kim [55] developed a system with a realistic 3D workspace representation of terrain, which has the capacity to provide interactive visual feedback to the operator of remotely controlled construction machines in order to make human-machine interaction more efficient. Other studies have focused on real-time monitoring and detection of the construction equipment in earthwork operations which is beneficial in several ways, such as productivity measurement and automated performance assessment, accident warning and locating resources in the construction site. For example, Azar et al. [56] introduced a vision-based system that detects the machines involved in loading actions, tracks them, recognizes their interactions, and estimates the cycle times; Azar and McCabe [57] presented two promising approaches combining available image and video processing methods to locate and distinguish dump trucks from other earthmoving machines in noisy construction videos; Memarzadeh et al. [58] presented a computer-based vision algorithm for automated 2D detection of construction workers and equipment from site video streams; and Golparvar-Fard et al. [59] presented a computer based vision method for equipment action recognition. Concerning spatial accuracy, Vahdatikhaki et al. [60] presented a novel approach to improve the quality of data captured by less expensive real-time location systems so that the location of the equipment can be accurately estimated.

3.6. Innovation

Papers in this theme deal with construction equipment development and applications of hybrid systems in construction machinery. Concerning equipment development, new methods and designs are implemented to enhance reliability, machine control, comfort, safety and reduce costs derived from failures and breakdowns. For example, Chen et al. [61] presented a systemic analysis of the cushioning performance of the high-pressure cylinder of an excavator's arm that could be instructive to construction machinery designers and researchers, especially the high-pressure cylinder designers and the hydraulic system designers; Sun and Zhang [62] explored the characteristics and advantages of the hydraulic mounts used for vibration isolation of an earthmoving machinery cab compared with the rubber mounts; they found out that the cab system with quadratic damping hydraulic mounts are remarkably effective in mitigating the vibrations and in enhancing the cab comfort; and Solazzi [63] studied the boom and the arm of an excavator with the aim to replace steel alloy by aluminum alloy and thus reduce the weight of the machine.

However, the application of hybrid systems in construction machinery is the most popular sub-theme. Since advanced hybrid propulsion technology is the key to achieve fuel economy, construction machinery makers have put much effort in the research on applying hybrid propulsion techniques to further reduce fuel consumption and pollutant emissions. Lin et al. [64] presented applications of hybrid systems in construction machinery and highlighted the challenges encountered by the researchers and the construction machinery manufacturers, such as the high cost that needs to come down to the level of the conventional construction machinery with no sacrifice in performance. In the direction of energy saving and environment protection, Inoue and Yoshida [65] developed a hybrid system for a hydraulic excavator and Wang et al. [66] pointed out the trend of hybrid power loaders. Lin et al. [67] dealt with the method of how to regenerate the potential energy for a hybrid hydraulic excavator; and Hui and Junqing [68] proposed an energy saving scheme with parallel hydraulic hybrid system for a loader to capture the braking energy normally lost to friction brakes. Also, Wang et al. [69] in their paper analyzed the performance of the power train hybridization of hydraulic excavator and compared the main performance among the parallel,

the series and the conventional configurations and Xiao et al. [70] dealt with control strategies of power system in hybrid hydraulic excavator.

3.7. Environment

Construction equipment is a major source of greenhouse gases and other air pollutant emissions. The emerging concept of sustainable or green construction emphasizes the urgency of minimizing the harmful impacts on the environment [71]. Manufacturers of earthmoving machines must address sustainability requirements, as well as remain competitive. Considering environmental issues during the planning phase could increase project's value [72].

Lewis et al. [73] in their work introduced the challenges to quantification of emissions from non-road construction vehicles and described associated governmental regulations and incentives for reducing emissions. Zhang et al. [74] developed a simulation method to estimate the emissions and noise by reflecting the uncertainty, randomness and dynamics in construction. Heidari and Marr [75] employed a portable emission measurement system for real-time emission measurement of construction equipment under actual operating conditions on site, to find out that in some pieces of equipment there were large discrepancies between measured emissions and those predicted by widely used models. Hajji [76] proposed a methodology for estimating fuel use and CO₂ emissions for some common earthwork activities performed by bulldozer, excavator and dump truck to help the contractor estimate the total expected polluting emissions for the project, which would be valuable information for a preliminary project environmental assessment. Selecting the most appropriate equipment concerning its environmental impacts is highly challenging. For this, Waris et al. [77] focused on determining selection criteria based on the fundamental concept of sustainability. In other papers, Ahn et al. [78] used low-cost accelerometers to measure the operational efficiency of construction equipment and monitoring environmental performance and Ng et al. [79] presented an eco-approach to enable operators to achieve optimal productivity for fuel efficiency of a hydraulic excavator. The research revealed that the combinations of various engine speed settings and bucket cut depths can increase productivity and reduce greenhouse gas emissions.

4. Discussion

In our era where civil engineering projects are more demanding in terms of more cost-effective solutions and environmentally friendly use of resources (construction equipment, materials, labor), the advancements in the CE industry focuses mainly in the following areas [80, 81, 82, 83]:

- Higher production rates with shorter cycle times and better performance
- Usage of several software applications for better CE management: increased productivity, efficiency, safety and operational analysis
- Innovations in remote diagnostics tools for proactive maintenance
- Ergonomic design that focuses mainly on the human being by offering better cabin conditions
- Remote control of the CE through the use of neural networks applications; the autonomous machine control and use of robotics ("unmanned" equipment)
- Fewer gas emissions by using hybrid engines
- Usage of lightweight materials for construction and hence better performance with lower fuel consumption

All the previously mentioned issues are well established in the literature of the last decade. Research concerning optimization tends to focus on operational analysis regarding the use of the appropriate fleet selection for specific construction method, time and cost constraints. Collection of performance data, remote control of proactive maintenance, automation and "unmanned" machines also attend to the demands for lower construction costs. Regarding the maintenance/downtime theme, condition monitoring helps to accurately assess the performance and operating condition of critical equipment. Concerning the theme of productivity, research includes the integration of telematics for tracking machine location, fuel consumption, availability and idle time. Future research efforts are directed in utilizing state-of-the-art technology to provide real-time spatial and performance data for even more effective equipment management. Regarding the operator's competence, emphasis is given on the use of simulators and game technologies to safely train them and consequently advance their skills and enhance their levels of proficiency in a cost-effective way. Through the use of applications simulating worksites, the machine operators gain familiarization and understanding of machine controls, learn proper operating procedures and discover ways to maximize productivity. Regarding the theme of innovation, the design of hybrid engines has attracted a considerable amount of attention amongst researchers. The machine's ability to collect, store and release energy during operation, enables lower fuel consumption and the potential for increased productivity, while decreasing the amount of harmful emissions released into the air. Remotely controlled unmanned construction equipment is the new trend in R&A intending to automate the construction site, leaving humans to program and control the

project's progress. Where high reliability and resilience to harsh environmental conditions are required, unmanned construction equipment can play a valuable role. In this field, manufacturers going one step further, already investigate the co-existence of unmanned construction equipment and unmanned aircraft (drones that provide 3-D models of the terrain) for routine construction. Finally, regarding the protection of the environment, the holistic approach combines the efficient and effective operation and the application of the correct environmental policies. During the two last decades the European and American policies have determined the requirements for the limitation of air pollution. The use of new materials for energy consumption as the biodiesel, biogas and dimethyl ether constitute alternative, renewable energy sources. As construction industry faces increasingly restrictive environmental regulations, future research will strive to facilitate "cleaner" machines to meet regulatory requirements.

5. Conclusions

The main conclusions of this research can be summarized as follows:

1. The academic research work regarding CE over the last decade has focused on the following thematic areas:

a. Optimization, b. Maintenance / Downtime, c. Productivity, d. Operator's competence / Health and Safety,

e. Robotics / Automation, f. Innovation, and g. Environment.

- 2. The themes cannot be considered as completely distinct due to the interrelationships between them.
- 3. The areas on which the construction equipment industry has currently focused are embraced by the academic research community and vice-versa.
- 4. The advancements in technology have led to the use of remote control and maintenance systems improving the organization and controlling the performance of a construction equipment fleet. Moreover, R&A are working on "unmanned" machines that will do the job according to the requirements of the humans programming and controlling the project's progress.

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