

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

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RESEARCH ARTICLE

Received 09 December 2016

Abstract

A considerable body of literature has been dedicated to research studies on construction equipment. Many topics were discussed and analysed, and various conclusions have been reported. However, research papers published regarding 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 fields the academic research was concentrated on but would additionally reveal potential gaps for future research.

In the current study, through a systematic review of the academic literature published over the last decade, primarily identified via online databases, main research themes such as optimisation, maintenance/downtime, productivity, robotics and automation, operator competence, innovation, and environment are determined and discussed, with future research directions suggested. The outcome of this paper will facilitate future researchers to develop a body of knowledge of progress on construction equipment and its potential functions and provide future research directions on this issue.

Furthermore, some pointers will be provided regarding the optimum selection of fleet equipment as a key factor for the success of any construction project. These will be given as part of the necessary holistic and strategic approach required to deliver a construction project successfully.

Keywords

construction equipment, optimisation, productivity, maintenance, research, fleet, construction project

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 realisation of civil projects; it, therefore, represents a major capital investment for the construction industry. In this research, the term CE refers to the machinery used for earth-moving operations (for example, excavators, dump trucks, loaders, compaction rollers, graders, scrapers,). Those earthworks mainly consist of four basic processes: excavating, hauling, spreading, and compacting (Peurifoy and Ledbetter, 1985).

There is a lot of research work on CE. However, research papers published about CE, are highly diversified, and there is a lack of systematic analysis and classification. A previously organised research on this subject can only be traced in the review conducted by David J. Edwards and Gary D. Holt (Edwards and Holt, 2009). In their work, regarding future research directions, the authors highlighted the following:

Machine maintenance may develop more sophisticated predictive models that enable “just-in-time” component replacement.

Plant location and spatial data expanded to embrace large fleet management,

The concepts of autonomous machine control, automated systems and robotics might all be more inviting to researchers in the future given the advantages of “unmanned” machines,

The adoption of nanotechnology and the production of hybrids could be further possible avenues of development,

Given the above, an updated review on the latest published academic papers dedicated to construction machinery should not only reveal the direction of research but additionally, delineate 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 with the concluding comments.

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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, optimisation, research, earthmoving operations, were involved in the title, abstract or keywords of the articles searched. Papers derived from editorials, books review, forums, articles in the 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 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 many commonalities on account of the complex inter-relationships among them (Fig. 1). Moreover, it is acknowledged that the review is in no case exhaustive. The themes and number of papers falling within them are shown in Table 1:

Table 1 Number of papers falling within the seven Themes identified

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

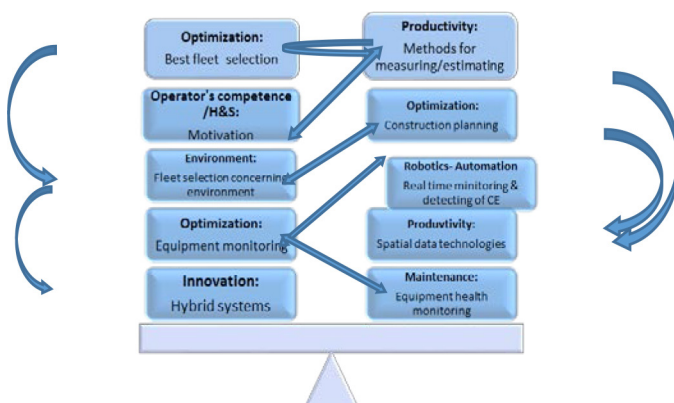


Fig. 1 Indicative interrelationships between sub-themes

3 Literature review

3.1 Optimization

Optimisation 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 use efficiency, minimise construction cost, reduce construction time and improve quality.

Construction project scheduling has received a considerable amount of attention over recent years, and many models have been developed. For example, Moselhi and Alshibani (Moselhi - Alshibani, 2009) developed a model that utilises genetic algorithm, linear programming, and geographic information systems (GIS) to support management functions. As such, Zhou et al. (2013) presented a review of the methods and algorithms that have been developed to examine the area of construction schedule optimisation. Appropriate fleet selection is a prominent issue, making it significant for many researchers. Zhang (2008) proposed an integrated framework for a multi-objective simulation–optimisation for determining optimal equipment configurations for earthmoving operations; Hola and Schabowicz (2010) 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. (2012) introduced a model that promises optimum selection of fleet equipment based on simple, economical operation analysis.

Contractors have also started to acknowledge and use telematics and other spatial technologies for timely collection of their equipment fleet data. This sub-theme has attracted particular interest amongst researchers. Said et al. (2014) presented novel methodologies to support heavy equipment fleet managers use telematic data in two major tasks: fleet use assessment and equipment health monitoring; Alshibani and Moselhi (2012) developed an optimization simulation model that uses a Global Positioning System (GPS) for fleet selection for earthmoving operations; Akhavian and Behzadan (2012) presented the results of a remote tracking technique developed to capture field data from construction equipment in real time that can be used to predict the performance of a construction system based on the latest status of the project; Pradhananga and Teizer (2013) presented the use of low-cost easy-to-install GPS data logging technology for tracking and analysing construction site operation of equipment resources. Overall, construction equipment management can improve construction project performance and contractor corporate performance; Samee and Pongpeng (2015) not only studied these relationships by collecting contractors' opinions but also examined the causal relationships between construction equipment selection factors and competitive advantage of contractors (Samsee and Pongpeng, 2016). Moreover, Aziz et al. (2014) presented a smart optimisation model, which incorporates the basic concepts of Critical Path Method (CPM) with a multi-objective Genetic Algorithm to support the balance between time, cost and quality simultaneously for mega construction projects. Finally, Shawki et al. (2015) displayed a tool for simulating earthwork operations with the ability to model all kinds of problems (deterministic, stochastic, discrete and continuous) in most applications of construction.

3.2 Maintenance / Downtime

Maintenance, as a system, plays a key role in reducing cost, minimising equipment downtime, improving quality, increasing productivity and providing reliable equipment and as a result, achieving organisational goals and objectives (2011). Downtime, resulting from machine breakdown during operations, is one of the most unanticipated factors that have a substantial impact on equipment productivity and organisational performance as a whole (1999). According to Kannan (2011), there are three repair philosophies that equipment managers adopt:

- Fixed Time-based Maintenance (FTM): replacement of a part occurs after a fixed time interval, irrespective of its condition
- Operate to Failure (OTF): replacement of a part occurs only after it has failed
- Condition-Based Maintenance (CBM): the ongoing condition of the part in question determines if it needs to be repaired.

CBM strategy which integrates machine data, prognostics and remote diagnostic tools represent the future of maintenance strategies. For this purpose, sensors are applied to detect changes in equipment components for contractors to gain insight into operations to understand machine health and avoid downtime and excessive maintenance costs. Chen et al. (2013) 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 construction machinery faults are related to their hydraulic systems. Equipment health-monitoring is a proactive maintenance tool to estimate the equipment's failure probability, and hence, Said et al. (2014) developed telematics-based equipment and 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. Prasertrunguang and Hadikusumo (2009) proposed a model that intends to facilitate a better understanding of the relationships among acquisition condition, operational practice, maintenance quality, disposal practice, and downtime consequence of heavy equipment; Marinelli et al. (2012) investigated the impact of various parameters (capacity, age, kilometres, maintenance) on the deterioration process of earthmoving wheel trucks using the discriminant analysis methodology. Similarly, Marinelli et al. (2014) presented an Artificial Neural Network (ANN) based model for the prediction of earthmoving trucks' condition level using the parameters above as predictors. As with certain other studies reported in this theme, Mohideen et al. (2011) introduced a model that handles the issues of unpredictable breakdowns in construction plant to minimize the breakdown time and enable a quick recovery

of the construction plant; the model derived the breakdown parameters from the previous history of the work records/environment. Mohideen and Ramachandran (2014) proposed a breakdown code management to provide a focused and unambiguous approach to the maintenance crew. Additionally, Yip et al. (2014) 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; Curcuru et al. (2010) proposed a methodology that minimizes maintenance costs by determining the time at which the decision must be taken and the date for starting the maintenance procedure.

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 (2006). Panas and Pantouvakis (2010), in their review research, explored the different perspectives for measuring or estimating it; while Yi and Chan (2014) conducted a systematic review of labour productivity in the construction industry. Productivity estimation is heavily affected by the type of operational coefficients and the estimation methodologies being considered. Based on this, Panas and Pantouvakis (2010) proposed a structured framework for comparing different productivity estimation methodologies and evaluating their sensitivity with operational coefficients variation for excavation operations. Rashidi et al. (2014) proposed a generalised linear mixed model to estimate the productivity of a common type of bulldozer and compared the outputs with the results obtained by using a standard linear regression model.

Telematics and spatial technologies were also used for estimating productivity in near real time. For example, Montaser et al. (2012) presented an automated method that utilizes GPS and Google Earth to extract the data needed to perform the estimation process; Montaser and Moselhi (2014) 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 research included that of Schabowicz and Hoła (2007; 2008) who applied ANNs not only to predict productivity but also to predict earthmoving machinery effectiveness ratios; Marinelli and Lambropoulos (2013) proposed a new algorithmic method for scraper load-time optimization; Oh et al. (2015) developed a driver model for the wheel loader V-cycle working pattern and a 3D dynamic simulation model to analyse the working performance and energy flow in each component. Finally, the work of Rustom and Yahia (2007) 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 (H&S)

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 H&S aspects. 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; consequently, Holt and Edwards (2015) identified the superlative role of operator competence in relation to other productivity variables. Concerning H&S aspects, training is widely considered to be one of the best approaches to accident prevention. Operator training simulators are a key component to serve the purpose of keeping plant operating safely, with optimal performance and reliability. 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 (2010). Guo et al. (2012) suggested the game technology based safety training method which provides trainees with an easily operated multi-user virtual environment to try and study different methods of operating the plant.

The inevitable coexistence of machinery and ground floor workers results in many work accidents on sites. According to McCann (2006), backhoes and trucks were involved in half the deaths, and rollovers were the main cause of death of heavy equipment operators. Hinze and Teizer (2011), 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. (2010) developed a novel blind spot measurement to help identify the blind spots of equipment, and to quantify and protect the required safety zone(s). Moreover, Marks et al. (2013) presented a technique based on laser scanning for measuring the blind spots of four different skid steer loaders. Teizer et al. (2010) 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 to unknown or other equipment. Similarly, Marks and Teizer (2013) presented a test method to evaluate the capability of proximity detection and alert systems to provide alerts.

The use of 3D visualisation not only assists equipment control but also improves operation efficiency and safety; consequently, Gai et al. (2013) introduced a real-time visualisation method to simultaneously assist heavy equipment operators in perceiving 3D working environments at dynamic construction sites. However, Su et al. (2015) warned that additional spatial information to the operator might 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 realise a competitive advantage (Pries and Janszen, 1995; Slaughter, 1998). A popular subtheme here is "unmanned construction", which is work performed by remotely operated construction machinery that corresponds to an operator controlled robot. In incompletely characterised environments with great exposure in hard and severe conditions, remote machine operation is the efficient solution for the operation of construction machines. Sasaki and Kawashima (2008), in their work, developed a remote-control system for a backhoe with a pneumatic robot system, while Kim et al. (2009) developed an excavator teleoperation system with the movements of a human arm. In a step towards facilitating the use of automated construction equipment, Seo et al. (2011) presented an excavation task planner devised to incorporate the intelligence of a construction planner and a skilful operator into the robotic control mechanism of an automated excavation system; Son and Kim (2013) developed a system with a realistic 3D workspace representation of terrain, which can provide interactive visual feedback to the operator of remote 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. Azar et al. (2013) 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 (2012) 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. (2013) presented a computer based vision algorithm for automated 2D detection of construction workers and equipment from site video streams, and Golparvar-Fard et al. (2013) presented a computer based vision method for equipment action recognition. Concerning spatial accuracy, Vahdatikhaki et al. (2015) 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. (2015) presented a systemic analysis method of the cushioning performance for the high pressure excavator arm cylinder that

could be instructive to construction machinery designers and researchers; Sun and Zhang (2014) explored the low-frequency advantages and characteristics of the hydraulic mounts used for vibration isolation of an earthmoving machinery cab compared with the rubber mounts, and Solazzi (2010) studied the boom and the arm of an excavator in order to replace the material from steel alloy to aluminium alloy and thus reduce the weight of the machine.

However, the application of hybrid systems in construction machinery is the most popular subtheme. Construction machinery makers have put much effort into research on applying hybrid propulsion techniques to further reduce fuel consumption and pollutant emissions. Lin et al. (2010) presented applications of hybrid systems in construction machinery and highlighted the challenges facing the researchers and the construction machinery manufacturers, such as the high costs that need to come down to the level of conventional construction machinery. Regarding the aspect of energy saving and environment protection, Inoue and Yoshida (2012) developed a hybrid system for a hydraulic excavator, while Wang et al. (2014) emphasised the trend in hybrid power loaders. Lin et al. (2010) dealt with the method of how to regenerate the potential energy for a hybrid hydraulic excavator, and Hui and Junqing (2010) proposed an energy saving scheme with a parallel hydraulic hybrid system for a loader to capture the braking energy normally lost to friction brakes. Wang et al. (2009), in their paper, also analysed the performance of the powertrain hybridization of a hydraulic excavator, and compared the performance among the parallel, the series and the conventional configurations; Xiao et al. (2008) dealt with control strategies of the power system in a hybrid hydraulic excavator.

3.7 Environment

The emerging concept of sustainable or green construction emphasises the minimization and elimination of harmful impacts on the environment (2000). Equipment manufacturers of earthmoving machines must address sustainability requirements, as well as remain competitive. Considering environmental issues during the planning phase could increase a project's value (Ahn and Lee, 2013). Lewis et al. (2009) 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. (2014) developed a simulation method to estimate the emissions and noise by reflecting the uncertainty, randomness and dynamics in construction. Heidari and Marr (2015) employed a portable emission measurement system (PEMS) for real-time emission measurement of construction equipment under actual operating conditions on site, while Hajji (2015) 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 pollutant emissions for the project.

Selecting the most appropriate equipment regarding its environmental impacts is highly challenging. For this, Waris et al. (2014) focused on determining selection criteria based on the fundamental concept of sustainability. In other papers, Ahn et al. (2013) used low-cost accelerometers to measure the operational efficiency of construction equipment and monitor environmental performance and Ng et al. (2016) presented an eco-approach to enable operators to achieve optimal productivity for fuel efficiency of a hydraulic excavator.

4 Criteria selection for onsite fleet construction equipment

The related issues of optimum fleet equipment selection to improve productivity are as old as equipment itself. As machines were involving in technology terms, so has our knowledge and ability evolved to understand and apply best construction methods for best construction equipment usage and improved productivity. The advent of computing and communication, as described in detail in the previous sections, has advanced the study towards the nuances of equipment productivity.

Today's high level of mechanisation of construction projects proves that construction machinery is vital for construction projects by achieving productivity and efficiency. During the construction phase, selection of the right equipment is a key factor in the success of any construction project. The decision on the use of suitable equipment for a given construction method is part of a holistic approach to a strategy that is necessary to deliver a construction project successfully. The appropriate selection of equipment has always been considered as a strategic decision during the construction phase of any project (Tatari and Skibniewski, 2006).

In the European Community, numerous Public Works are co-financed by European Union framework programmes. These programmes have strict budgetary rules and are highly time-constrained. So, it is an absolute necessity for the project client to adopt a coherent strategy for time-compression and cost minimization so that financial losses do not emerge. According to Lambropoulos (2006), a strategy that best approaches these demands extends overall project stages, from conception to commissioning, and incorporates widely accepted innovative methods and practices. Value Engineering, Constructability Review, detailed Work Breakdown Structure (WBS) are some of the methods that are used and incorporate the right allocation and selection of necessary resources (labour, equipment, material).

During the selection of construction equipment, there is a need for the most rational criteria that have a positive impact on operational efficiency, productivity, cost minimization as well as environmental and human well-being. The primary agenda of the equipment selection process is to achieve higher productivity, more operational flexibility and viable economic

considerations. With the growing industrialisation and mechanisation, this is getting even more important and complex for companies to assess and make the best decision from a pool of many alternatives. This is illustrated by the amount of research that such an issue has attracted and that has been carried out to improve mechanised construction practices. Selection of equipment is typically made by matching equipment in a fleet with tasks. This procedure usually takes into account equipment productivity, equipment capacity and cost. The following table summarises the research undergone concerning the different criteria that affect the decision processes when selecting the appropriate equipment for projects' activities.

Table 2 Precedent research on criteria selection for the best construction equipment selection

Chan and Harris, 1989	Best selection of backhoes and loaders based on technical criteria
Chan et al., 2001	Technical, economic criteria on the selection of material handling equipment
Bascetin, 2003	Decision supports systems for the selection of open pit mining equipment
Goldenberg and Shapira, 2007	Tangible criteria (technical, cost and site issues), Intangible criteria (safety, market, environmental issues)
Yan et al., 2009	Greenhouse gas emissions
Vorster, 2009	Construction equipment economics
Kannan, 2011	Productivity and maintenance
Chamzini and Yakhchali, 2012	Technical and cost criteria

5 Discussion

Today, where civil engineering projects are more demanding regarding more cost-effective solutions and the environmentally friendly use of resources (construction equipment, materials, labour), advances in the CE industry focus mainly on the following areas (Anon. 2016a; 2016b; 2016c; 2016d):

- Better production rates with shorter cycle times and better performance
- Use of several software applications for improved CE management: increased productivity, effectiveness, 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 applicability of neural networks applications to autonomous machine control and use of robotics ("unmanned" equipment)
- Less gas emissions by using hybrid engines

- Usage of lightweight materials for construction and hence better performance with less fuel consumption

From the literature of the last decade, all the previously mentioned issues are well understood. Research concerned optimisation has tended to focus on operational analysis regarding appropriate fleet selection for a specific construction method, time and cost constraints. Data collection for the performance of the equipment, remote control of proactive maintenance, automation and "unmanned" machines could respond 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 aspect of productivity, research included the integration of telematics for tracking machine location, fuel consumption, availability and idle time. Future research efforts are directed to utilising state-of-the-art technology to provide real-time spatial and performance data to further support effective equipment management.

Respecting the aspect of operator competence, emphasis is given to the use of simulators and game technologies to safely train operators and consequently advance their skills and enhance their levels of proficiency in a cost effective way. By joining simulated work site applications with realistic controls, the machine operators gain familiarisation and understanding of machine controls, learn proper operating procedures and discover how to maximise productivity. With regards to 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; the intention being to automate the construction site leaving humans to programme and control the project's progress. Where high reliability and resistance to harsh environmental conditions are required, unmanned construction equipment can play a valuable role. Regarding this issue, manufacturers, going one step further, are already investigating the coexistence of unmanned construction equipment and unmanned aircraft (drones that provide 3-D models of the terrain) for routine construction. Lastly, the construction industry faces increasingly restrictive environmental regulations; future research will strive to facilitate "cleaner" machines to meet regulatory requirements.

All these thematic areas of research and innovation concerning CE, focus on the necessary steps that should be taken regarding optimum fleet selection for projects. The principal criteria that determine fleet selection are productivity, lifecycle cost, equipment capability, and environmental impact.

6 Conclusions

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

1. The academic research work regarding CE over the last decade has focused on the following thematic areas:
2. Optimization; Maintenance/Downtime; Productivity; Operator's competence /H&S; Robotics/Automation; Innovation; Environment.
3. The themes cannot be viewed as discrete items regarding the interrelationships between them.
4. The areas on which the construction equipment industry has currently focused are embraced by the academic research community and vice-versa.
5. The advancements in technology have led to the use of remote control maintenance systems that better organise and control the performance of construction equipment fleet. Moreover, R&A are working on "unmanned" machines that will carry out the operations the humans will program and control the project's progress.
6. Regarding the selection criteria for construction equipment productivity, ownership and operational cost, residual value, maintenance costs, efficiency, equipment capability and environmental impact are becoming increasingly important

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