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EARTHWORKS CONTROL AUTOMATION

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Table of Contents

Executive Summary	1
Enhancing Efficiency of Earthwork Processes	2
Technical Approach	3
Use Case – Heysham to M6 Link	7
Data Analysis	8
Data Collection Requirements	9
Conclusion and Further Work	10
References ..	13

Executive Summary

Earthwork processes are influenced by a wide range of factors, including varying soil and weather conditions, machine related factors, traffic conditions, local site constraints and other human related factors. Dumpers and bulldozers are heavy duty equipment and there is need to optimise their operational efficiencies. Given dynamic nature of site and changing weather conditions, like temperature, precipitation or wind, can lead to process disturbance like complete restrictions on the site roads or a considerable slow down. Therefore, it is necessary to capture accurate data from site operations to reduce waste in earthwork processes.

Even though various commercial vendors (e.g. Lecia, Trimble) have started to provide commercial solutions to allow telematics operations (e.g. remote support, fleet management, grade control), costs of these solutions are prohibitive. Presented research proposes the use of low cost data capturing techniques and off-the-shelf technology components to collect real time and reliable data on Earthworks processes.

This research aims to enhance earthworks efficiency through better utilisation of building vehicles and an improved information flow. On-site observations and anecdotal evidence suggest that waiting time for excavators and dumpers on Highways Agency's schemes is a common occurrence. However, despite this evidence, there is a lack of real-time or archival data available on site operations and not enough effort is spent on gathering reliable and accurate data. In order to enable an optimised process, the need for an automated real-time data collection on construction sites is apparent.

Enhancing Efficiency of Earthwork Processes

The earthwork processes are influenced by many different factors. The performance of an excavator can be affected through a wide range of factors (Fig 1). Machine-related restrictions or failures can occur or the performance impaired by human factors e.g. an inexperienced dumper or bull dozer operative. Weather influences in terms of temperature, precipitation and also wind. They play an important role, as they can lead to a disturbance in the processes and to complete restrictions on the site roads or a considerable slow down.

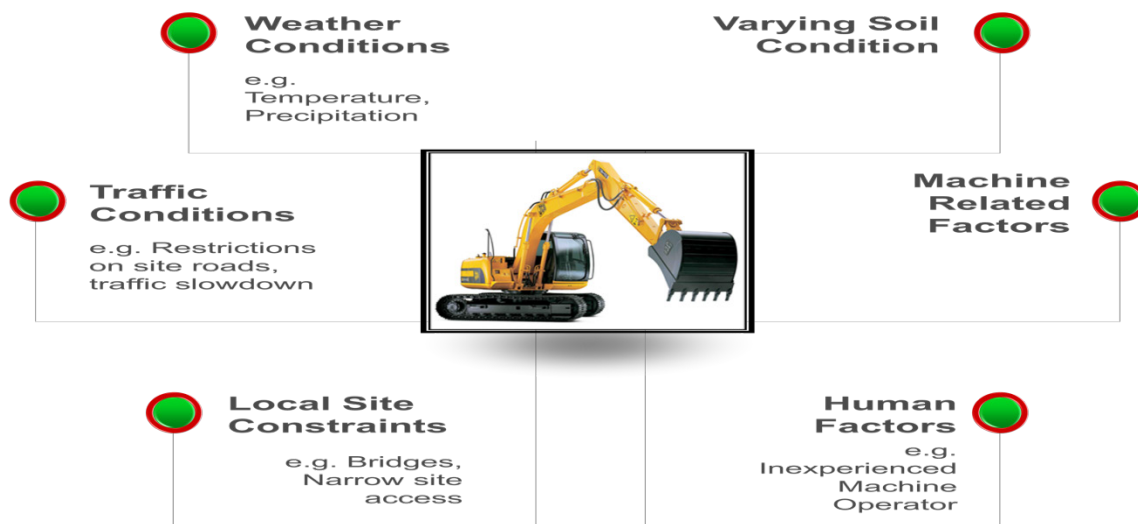


Figure 1 - Variables Affecting Earthworks Efficiency

This research aims to improve the efficiency of Earthworks operations through better utilization of the Heavy duty vehicles and an improved information flow. Anecdotal evidence, site observations and informal discussions with site staff reveal that waiting times for excavators, as well as dumpers, are a frequent occurrence. Hardly any real-time data is available and not enough effort is spent on gathering reliable data. The need for an automated data collection on construction sites is apparent in order to enable a real-time management.

The objective of this research project is to create a proof of concept for monitoring operation of construction vehicles using low-cost methods including real-time GPS data. The aim of this research is achieved through the following steps:

1. A requirements analysis to gain a deeper understanding of the current processes of an earthwork construction site,
2. Development of an application for Android for manual data input and of a Construction Monitoring Tool to visualize these data,
3. Testing as well as demonstration of the applications,
4. Prototypical data collection on a earthwork construction site and adoption of the application regarding the test results,
5. Evaluation of the developed system,

6. The use of modern communication techniques such as Material Requirements.

The use of modern communication techniques such as Material Resource Planning (MRP) or Enterprise Resource Planning (ERP)-Systems is standard within the manufacturing industry and has long been deployed with tangible efficiency gains. Transferring these techniques to the construction industry seems promising. However, such systems are highly dependent on consistency within the production processes, which is often difficult to achieve in site-based processes. Accurate data from site operations can be used to support daily, as well as weekly planning, to provide better control of projects. A higher level of transparency will most likely reveal a potential for further optimisation. The research process (Fig 2) involved establishing a control centre, real-time monitoring of site activities, identification of abnormal conditions and supporting a decision support framework for corrective actions.

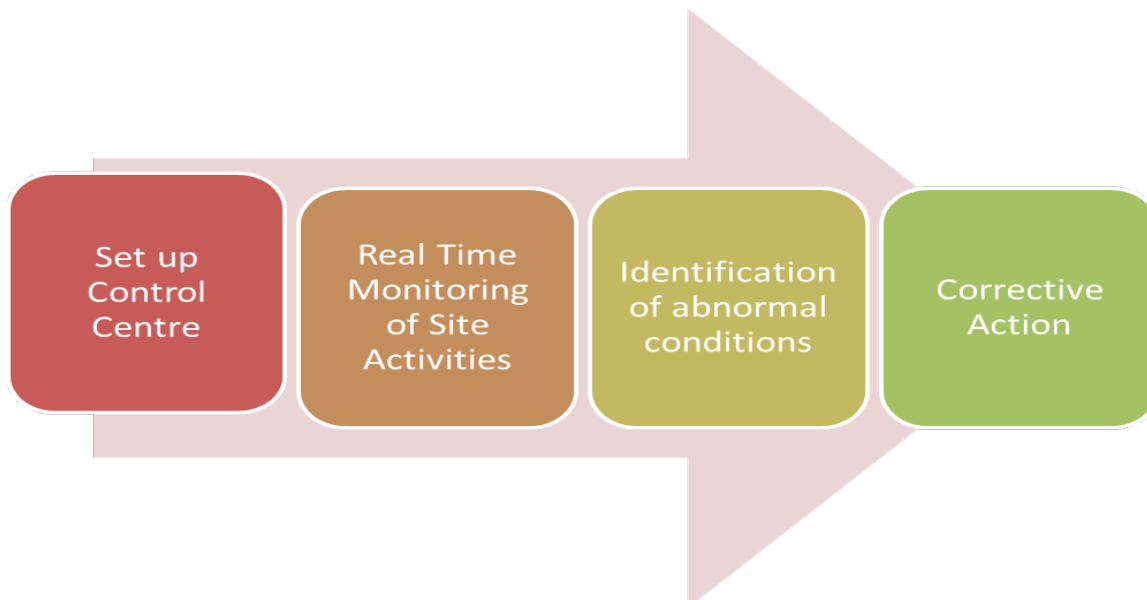


Figure 2 - Research Process

Technical Approach

The basic idea is to set up a higher-level control centre, which allows real-time monitoring of the construction site. Abnormal conditions can thereby be detected, making a quick response possible. A higher level of transparency regarding the current events on the site will provide the construction manager with the possibility of making more reliable decisions. Without accurate site data and insufficient level of transparency, decisions are often based on conjectures and assumptions. These assumptions and the decisions made therefore could be wrong and inappropriate.

The technical foundation and requirement to make this system work is to equip the building vehicles with integrated sensors of two kinds; GPS-sensors with increased accuracy and additional sensors to collect the exact position and orientation of the excavator bucket or the

dozer blade. A construction-site-wide communication platform has to exist to retrieve this data in real-time.

An ideal circumstance would require all excavators and dozers to be equipped with the described sensors. A preliminary examination interview with developers and producers of those sensors was conducted to reveal that the costs for this type of sensors vary between 30,000 £ and 60,000£ depending on the machine type and producer. All building vehicles, including the transport vehicles, need to be connected to the communication platform amounting to additional 4,000 £ per vehicle. These costs include the installation of the equipment and the training of the drivers.

Considering that this solution is rather expensive a lighter and more advantageous prototype is being targeted. The minimum configuration would only require knowledge about when the loading and unloading of a dumper begins and ends. This could be achieved through manual input by the driver into a device like for example an Android mobile phone equipped with a GPS sensor. The performance of the excavators on the other hand could be estimated by the number of loaded dumpers. These data can be used as a first step, to analyse the current situation of the construction site.

The approach adopted involved the use of a mobile prototype with a manual data input by the drivers, as it is a cost-efficient solution. This implies risks in the following areas:

- accuracy of GPS data,
- accuracy of manual data input,
- reliability of manual data input and
- Network coverage.

The concept of the developed prototype is shown in Figure 3, which also refers to the techniques used. In the prototype, drivers of construction machines are able to send their current status including a GPS position to a server, where it is persistently saved in a MySQL-database.

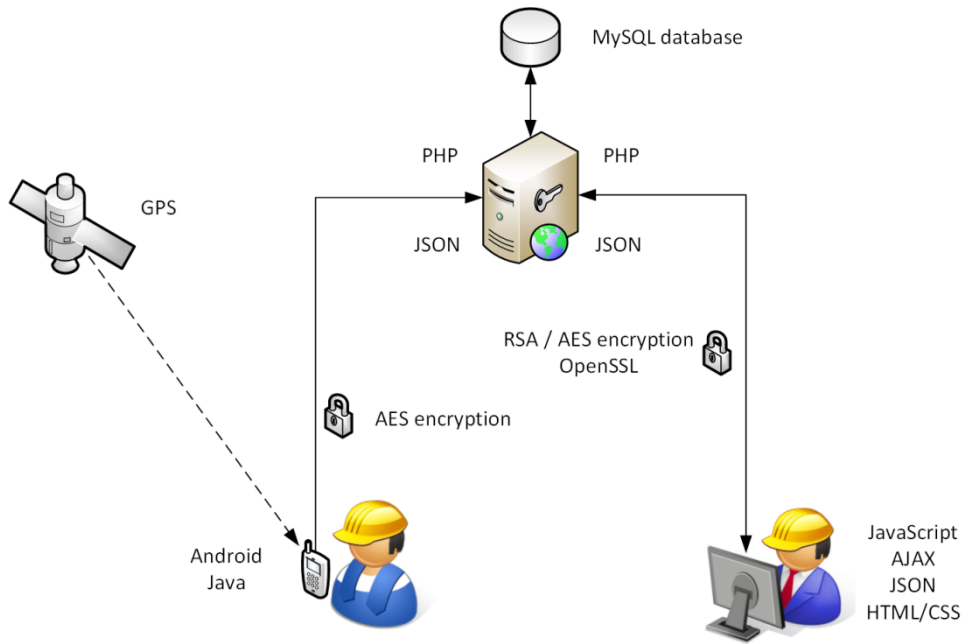


Figure 3 - System Architecture

The interface of the mobile application, after a user logged in, is shown in Figure 4. The application is programmed for Android, an open-source mobile operating system, using the object-oriented programming language Java. The arrangement of the controls is context-sensitive considering the current state. For instance, “driving” is the next logical step after “loading” and “unloading” follows.

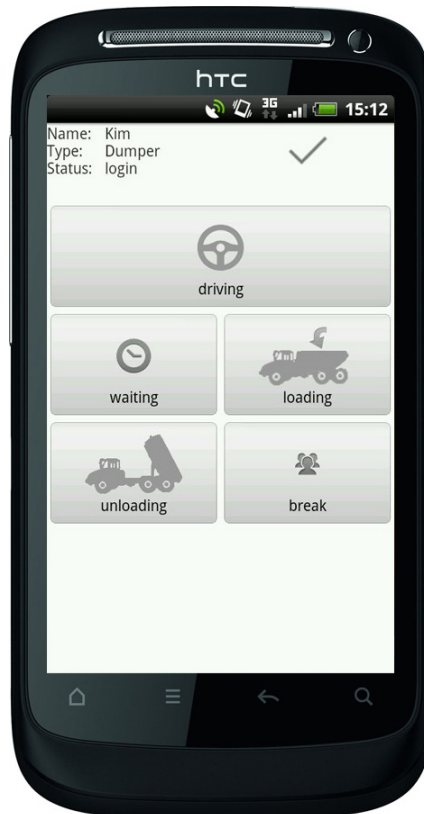


Figure 4 - Android Application for Construction Machine Drivers

The construction manager is able to login by using his/her username and password to the server via the web and retrieve real-time data as shown in Figure 5 and Figure 6. Up-to-date information is automatically loaded in the background through “asynchronous JavaScript and XML” (Ajax) and the visualisation is updated accordingly. This visualisation can be adapted to the needs of the construction manager, who is able to use filter mechanisms to hide and show different kinds of information. Moreover, position-based data can easily be displayed by clicking onto a construction machine or a corresponding GPS position. An analysis of the collected data, the average loading cycle time or proportionate waiting times for instance, can then be calculated.



Figure 5 - Data were Collected on Vehicle Location, Loading Cycle Time and Wait Time

In consideration of the sensitivity of the transferred data, which are mainly performance data, the entire communication is encrypted by using the Advanced Encryption Standard (AES). Within the web interface, the exchange of the AES-keys is carried out by the RSA cryptosystem (by Rivest, Shamir and Adleman). Each data package between the mobile phone and the server as well as between the web interface and the server is transmitted by using the data format of the JavaScript Object Notation (JSON). This standard provides a very compact syntax, which allows an easy data exchange between the applications and requires very little computing time.

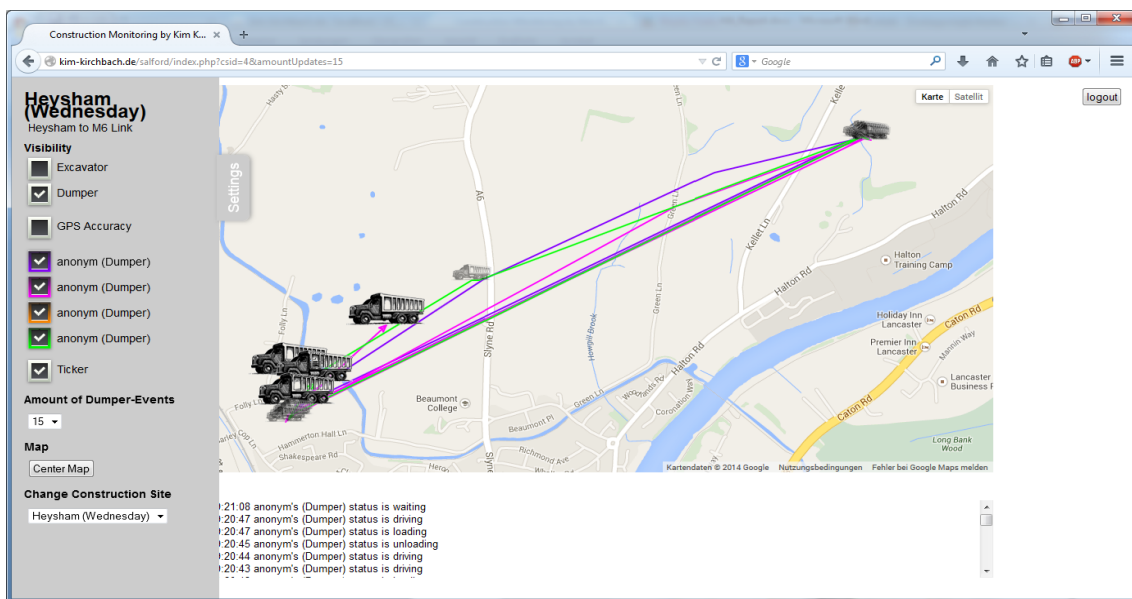


Figure 6 - Web Interface for the Construction Manager

The developed prototype enables a simple, real-time data collection system on construction sites and therefore, gives the construction manager the possibility to gain an overview of the current situation. Thus, an improved management of the processes can be realised and timely actions and precaution can be taken.

Use Case – Heysham to M6 Link

The construction site “Heysham to M6 link”, next to Lancaster, serves as a use case.

Following an email and a phone contact, a meeting on the site itself took place on July 14th. The planned use of the prototype was presented and further details were discussed.

As there was an on-site “no phone” policy, the safety personnel was also included. As a result, the developed app was modified to increase safety: All other applications on the phone were locked and could therefore not be used. The screen does always stay awake and illuminated. It was agreed that the dumper drivers are to be clearly instructed and are only allowed to use the phone while they are standing. Every “click” on the app is to be performed before the corresponding process starts and when the vehicle is standing still.

It was also agreed that the gathered data will be used within this report, with reference to the Heysham site, but with no connection to the dumper drivers. If an academic publication is to be written, it will make no reference to the construction site or the drivers.

After the confirmation by the site responsible, five mobile phones (the Motorola Moto G) were bought. It was agreed to start the case study at the end of July 2014 but due to the internal site processes, it had to be postponed to the mid of August.

On August 19th, a preliminary test was conducted. The application was tested several times during the development process but an on-site test was desired to see how the system works in a realistic environment. A side production line, where two dumpers serve one excavator,

was chosen. The test was carried out successfully, all data communication worked and the data were collected.

On August 20th and 21st, four dumpers of the main production line were equipped with the phones and data were collected for two days. In the following section a short summary of the collected data will be given.

Data Analysis

The connections between the mobile phones and the database worked and an overall of 1441 process steps were collected. A revision of the collected data was necessary to patch mistakes like missing data that occur when a driver forgets to click a button.

The data of the preliminary tests present the circulation time to be very stable. The average time of circulation between the loading and unloading is 11:57 minutes with a standard deviation of 01:21 minutes.

Table 1 and Table 2 show an extract of the data from Wednesday and Thursday. They show the average loading time as well as the standard deviation for the loading cycles for every dumper. Additionally, they present the amount of cycles entered and the amount of cycles that are evaluable, as it sometimes occurred that a process step is missing or was entered multiple times within a couple of minutes.

Table 1 - Evaluation Wednesday

Dumper Number	Evaluable Loads (Entered Loads)	Average Time (mm:ss)	Standard Deviation (mm:ss)
1	11 (15)	13:55	02:22
2	9 (14)	12:02	01:01
3	10 (14)	13:24	01:11
4	7 (12)	12:15	00:57

Table 2 - Evaluation Thursday

Dumper Number	Evaluable Loads (Entered Loads)	Average Time (mm:ss)	Standard Deviation (mm:ss)
1	12 (14)	12:43	01:33
2	12 (13)	11:25	01:06
3	14 (15)	13:15	01:52
4	14 (16)	12:27	02:42

As the data indicate, the loading cycles are also very stable on the main production line. A closer look at the waiting times, as presented in Table 3, indicates that the dumper drivers did not track the waiting times properly. On-site observations lead to the assumption that the data of dumper 3 and 4 are more likely to be accurate than of dumper 1 and 2.

Table 3 - Evaluation Thursday: Waiting Times

Dumper Number	Collection Duration (hh:mm)	Working Time (hh:mm)	Waiting Time (hh:mm)	Proportionate Waiting Time
1	06:08	05:38	00:26	7,69%
2	05:44	05:14	00:00	0,00%
3	05:54	05:24	00:48	23,53%
4	05:17	04:47	00:27	25,23%

Further investigations are necessary to determine the right waiting time proportion. Nevertheless, the data along with the observations show potential for an on-site optimization. Especially in consideration of the particularities of the site (e.g. the bridge, which only allows one dumper per time, or the crossing of the busy road with traffic lights) an adaption of the logistics within the site promise some benefits.

Data Collection Requirements

There are two key requirements for setting up Android Application:

1. Mobile phones with the Android operating system (minimum version 2.3) as well as a mobile data connection and
2. a server, capable of handling the PHP and MySQL technologies, to store the incoming data. The corresponding PHP files have to be copied to the server and a database has to be created.

It is also recommended to use car holders so that the dumper drivers can adjust the mobile

phones in their cabin according to their needs. Apps like Applock¹ should be used to lock the whole device except for the data collection app as to avoid that dumper drivers using the mobile phones during their work times. This precaution not only affects the distraction of the drivers regarding their work performances but is also a necessity for site safety.

The collected data can be exported from the database, into for example a CSV- or Excel-file, enabling a detailed analysis. It should however be considered to use MySQL and PHP for this process as for the high amount of possibilities regarding data queries and analysis as well as reduced computing time. The development of an PHP-Analysis-Tool should also be taken into account. For a non-prototypical use, it is also recommended to implement some filter mechanisms in order to detect logical errors within the dumper processes caused by a missing or wrong input of the drivers.

Conclusion and Further Work

Most construction sites show a significant potential for improvement. Especially the area of earthworks is characterised by huge dynamics and uncertainties. The combination of a successful use of information systems as well as modern communication techniques together with the profitable application of lean management methods of construction does promise a more efficient and effective design of earthworks processes.

Summarising this work so far, it can be concluded that the use of a construction site control centre for earthworks and therefore, the connected application of some lean management principles, especially the *kanban* pull system, is very promising and presents a great opportunity to improve processes on earthwork construction sites in the future.

Due to privacy considerations, no dumper drivers were linked to the mobile phones or the data. However, on-site discussions revealed that the managers showed a high level of interest regarding this matter in order to compare the performance over several days.






The manual input of the data requires efforts from the dumper drivers and even though most of them were very friendly and helpful, some of them were unhappy with the necessity of clicking before performing an action. The possibility of implementing an automatic data collection system could be considered. As discussed earlier, a fully automated system is very expensive but it could be examined if only the GPS position itself would enable conclusions regarding the on-going processes. This would require more professional equipment with highly reliable and accurate GPS receivers, but with the position of all machines, it might be possible to receive similar results (a dumper with a ten meter radius means “loading”, two dumpers indicate that at least one of them is waiting etc.).

A more detailed analysis of the data is required. Not only can several statistics be created but also situations, which hold significant optimisation potentials, can be identified. Interviews with the managers on-site reveal that they are very interested in the real-time data and their visualisation as well as the possibilities of data evaluation by the database. Some evidence of improvements in earthworks processes, as gathered from the literature, is presented

1 <https://play.google.com/store/apps/details?id=com.domobile.applock>

in Table 4.

Table 4 - Potential Return on Investment

Benefit Realization	Source	Indicator	
18.3% Productivity increase in Excavators equipped with sensors, when compared with non-equipped machines	(Grimescheid, 2010)	18.3% Productivity increase	
In a simple trench construction work, the sensor fitted excavator saved 22.93% of time	(Adhalsteinsson 2008)	22.93% time savings	
Lower deviations in formation levels and grades, from actual plans, leading to stable process chain	(Sturm and Vos, 2008)	Quality improvements	
Implementations of the pull principle and Kanban systems in allocation of trucks to a road paver	(Kaiser and Zikas 2009)	86% reduction in truck idle time	
Using a combination of machine sensors, dozer and graders, gained a performance increase of 101%	(Caterpillar Inc, 2006)	101% performance increase	

These data can be used to identify on-site bottlenecks and incidents and form the basis for the implementation of new logistics concepts like the *kanban* system. Quantitatively, the effects of digital *kanban* could be shown based on stochastic simulations². In comparison to the currently used static variant of dumper allocation, a reduction of variance and therefore, an increased process reliability can be achieved by applying digital *kanban*. Minimizing the waiting times of not only excavators but also dumpers and dozers would result in an increase in performance. This, on the other hand, leads to reduced operating times of the construction machines, allowing for the possibility of an earlier use of those construction machines on another construction site. Therefore, the cost effectiveness and performance will be enhanced.

² see K. Kirchbach, L. Koskela and F. Gehbauer: *Digital Kanban for Earthwork Site Management*. In: Annual Conference of the International Group for Lean Construction – Understanding and Improving Project based Production, pages 663–676, B.T. Kalsaas, L. Koskela and T.A. Saurin (editor), Oslo, Norway: IGLC and Akademika forlag, 2014.



Key Benefits Realised

Figure 7 - Summary of Potential Benefits

The developed prototype was successfully used on a construction site and the collected data were visualised, which enables an easy understanding of the current situation on site. The data itself help the managers to adapt the processes on the construction site, based on accurate information, in order to optimise the overall performance.

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