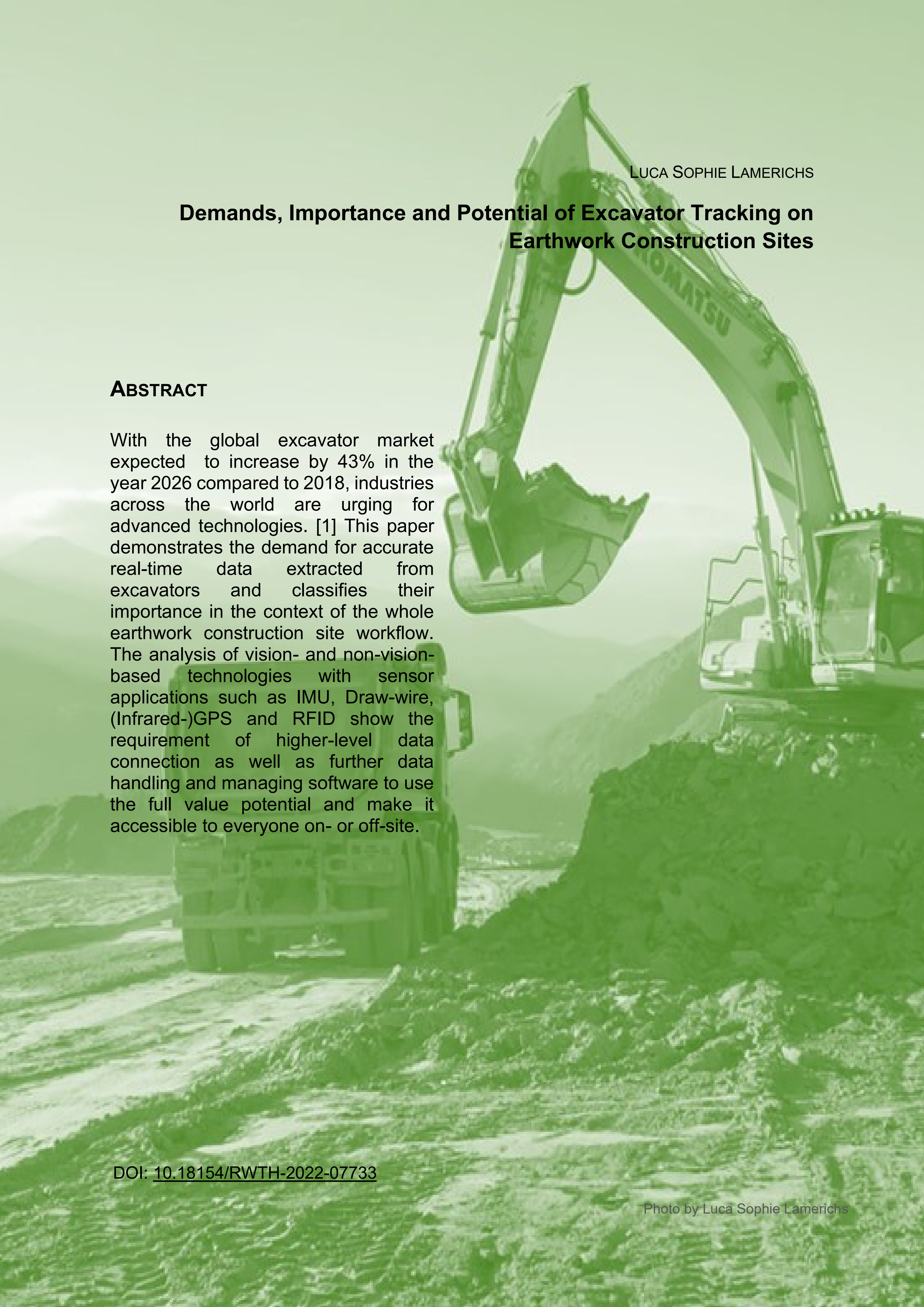

Luca Sophie Lamerichs

# Demands, Importance and Potential of Excavator Tracking on Earthwork Construction Sites

## Abstract

With the global excavator market expected to increase by 43% in the year 2026 compared to 2018, industries across the world are urging for advanced technologies. [1] This paper demonstrates the demand for accurate real-time data extracted from excavators and classifies their importance in the context of the whole earthwork construction site workflow. The analysis of vision- and non-vision-based technologies with sensor applications such as IMU, Draw-wire, (Infrared-)GPS and RFID show the requirement of higher-level data connection as well as further data handling and managing software to use the full value potential and make it accessible to everyone on- or off-site.

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Photo by Luca Sophie Lamerichs

# 1. Introduction

## 1.1 Motivation

As users browse the web, their online behavior is usually observed and tracked. Through this sort of complex tracking, websites are able to optimize and personalize the user's experience. [2] Looking at the history of excavators they have been used in construction industry for around 140 years [3] but they are still lacking in optimized performance on construction sites and the quality is dependent on the operator's skills. [4] While the global excavator market is expected to grow up to 63.14 billion US Dollar by 2026, which translates into a 43% increase compared to 44.12 billion US Dollar in 2018, the "Construction Industry is expected to drive the market of Excavators." [1] Technologically upgraded equipment is demanded by industries across the world. [1]

Therefore, the question arises, which potentials are hidden behind the tracking of excavators and the processing of this data.

## 1.2 Goal

The goal of this research is to screen out the potential information that can be extracted from excavators with the help of existing technologies and what this data can be used for to satisfy the information demand of earthwork construction sites. Furthermore, the goal is to determine the relevance of this data in context of the whole construction chain.

## 1.3 Research Framework

The first part of this paper describes the typical earthwork construction workflow, which is significant to understand the importance and relevance of the excavator tracking data in context.

The second part depicts the demand of information extracted from excavators on earthwork construction sites from a project manager's point of view that explains in depth the importance and relevance of these data in context of a typical earthwork construction workflow.

Subsequently, existing measuring technologies to determine the bucket position and orientation are described and their gathered data accuracy evaluated. Further requirements and possible solutions towards Data Handling and Accessibility are expressed.

The last part gives an outlook on necessary research, technologies as well as strategies to optimize the whole construction chain with excavator tracking.

# 2. State of the art - Earthwork Construction Workflow

Two main processes represent the earthwork constructions: Cut and Fill. The Cutting process consists of three subprocesses: excavation, loading and transportation, (Fig.1, 1.1-Cut) whereas filling and condensing form the Filling process. (Fig.1, 1.2-Fill) The default of regulations regarding excavated materials from the Cutting is the direct reuse of this material for backfill, fill for embankments or other parts on the same construction site. (Pic.1) Therefore, the Filling is highly dependent on time, material and information from the Cutting process. (Fig.1) [5, Ch. 343.00] Decisions for work activities and required resources contribute a major component to the success of the project in terms of costs, time, safety and quality. [6]

Picture 1: Material reuse for embankment filling on the same construction site (picture taken at PORR, Sibiu)

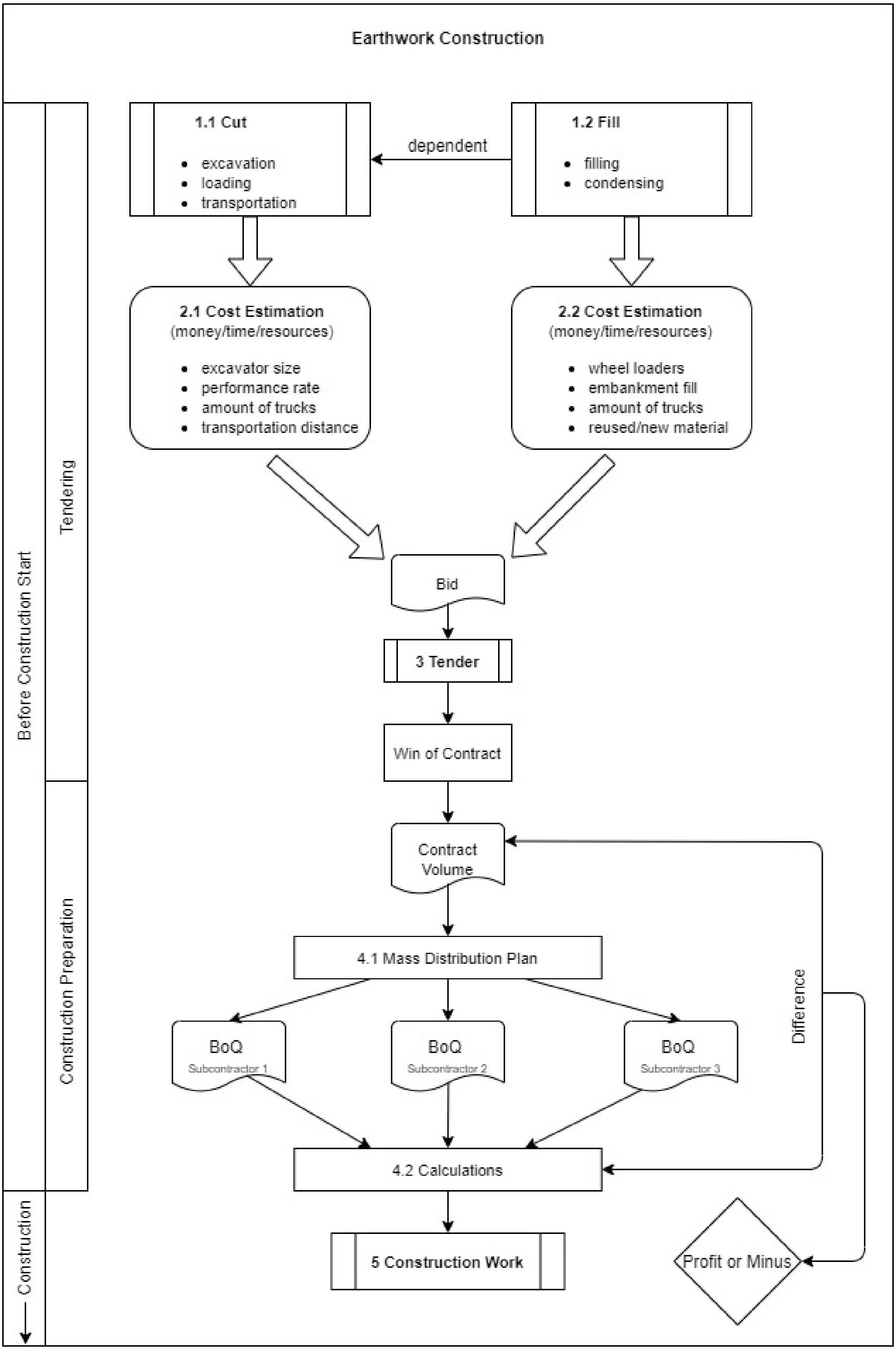


Figure 1: Earthwork Construction Workflow

As demonstrated in Fig. 1 (2.1 – Cost Estimation) these decisions are initially determined in the tendering phase of a project for a cost estimation, which includes money as well as time and resources. The accuracy of these estimations is "essential […] to both submit an accurate bid that has the potential to win a contract and to properly manage the resources assigned to the project so that [it] shows a profit." [7]

Based on these estimations a mass distribution plan and Bill of Quantities (BoQ) for potential subcontractors are established. (Fig. 1, 4.1-Mass Distribution Plan). Managing the respective compliance during construction is the responsibility of the site manager and ensures the success of the project. [7]

## 3. Methodology

For the importance of presenting real everyday problems with regard to information demand on the construction site, interviews with long-time experienced site, execution and operational managers of earthwork construction sites are held, a workflow diagram developed, and their construction site demands on information filtered out. With these key demands existing research is examined to find technologies that can extract valuable data from excavators for these purposes. Potential information of these technologies and their importance in the workflow context is analyzed. The results are combined and compared to the demands to identify the compliance and gaps of technologies. Requirements for future research, technologies and strategies are discussed. (Fig. 2)

## 4. Results and Discussion

### 4.1 Demands and Importance

To define the most valuable data and determine missing technologies to extract these, a closer look on the workflow is necessary.

Fig. 3 demonstrates a typical management workflow of earthwork construction sites as described by a site manager with many years of experience. Two influencing factors can be seen: first, the length of time period $t_c$ and $t_s$, which influence the reaction time and the ability to initialize required action when needed. (Fig.

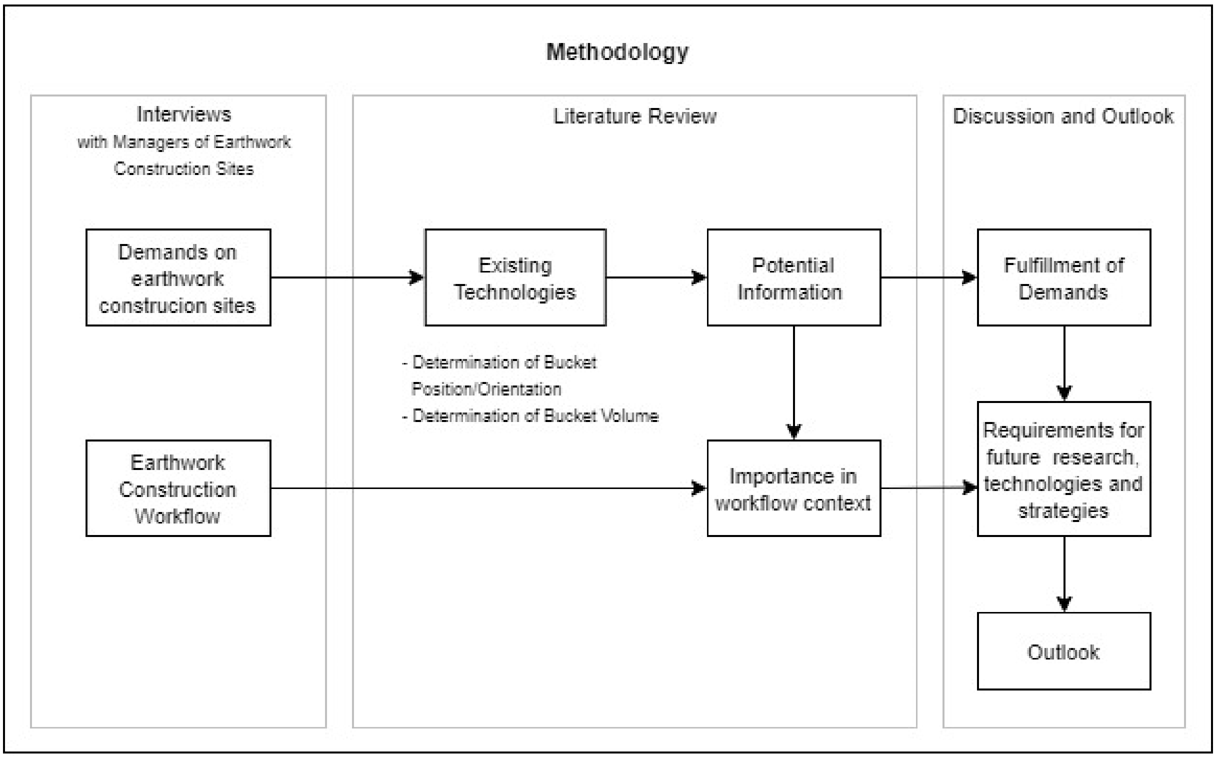


Figure 2: Methodology

3, 7-Take Action / Required Changes) and second, the quality and accuracy of the data extracted that is compared with the calculations. This influences the correctness of the construction site progress and the billing of the subcontractors. [8] Estimating the actual productivity and constantly updating the construction site progress are essential elements to predict the adherence of estimated resources. Research studies show that the data collection, storage, retrieval and analysis with manual methods, such as a manual surveying of the excavated surfaces or volumes (Fig. 3, 6-Surveying), are “prone to human error and may result in delayed corrective actions with undesirable cost consequences.” [8, p. 1011] In practice the actual productivity of excavators is estimated by multiplying the number of filled truck loadings and their capacity. [9] Further studies use vision-based motion analysis to calculate the performance rate of the excavator and multiply these with the bucket capacity. [10]

According to the interviewed managers all these estimations are insufficient, considering the frequency of movements of these machines and thus the ensuing multiplied deviation to the real volume. These deviations are caused by constantly

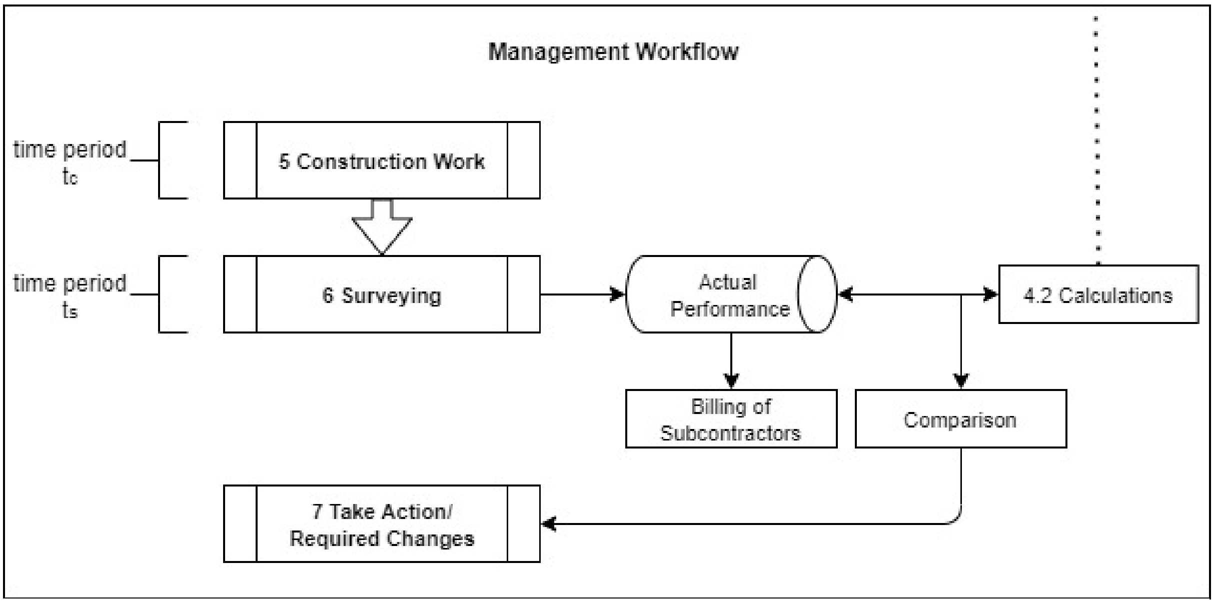


Figure 3: Earthwork Construction Management Workflow

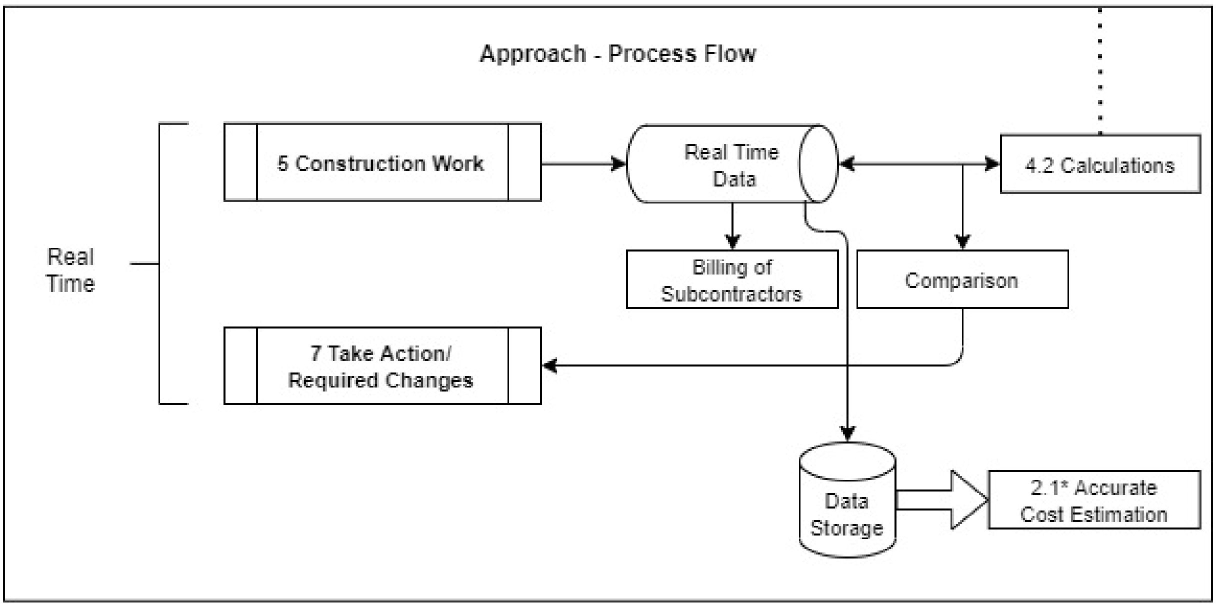


Figure 4: Approach Earthwork Construction Process Flow

changing bucket volumes due to motion and orientation changes. For clarification, the example of a movement with an empty bucket is given by a manager, which would be included as performance, although the value of this performance is zero.

Therefore, a different approach is presented in Fig. 4 to eliminate the decision failure due to insufficient information about the actual performance and the time delay of the information exchange.

With the help of the following technologies, Real Time Data from the excavators provide the actual performance, which is used directly for the billing of subcontractors. At the same time this performance is compared to the estimated calculations so that discrepancies are directly detected. (Fig. 4) With the help of these technologies site managers will be able to act before losing time and money, as for example, correct the optimal size of excavators, provide more trucks or reduce transport distances. (Fig. 4, 7-Take Action / Required Changes) Incidentally, the Data is stored and used to optimize cost estimations for future projects. As can be seen in Fig. 4 (2.1*-Accurate Cost Estimation) this could influence the whole project planning and execution from better bids for tendering to fewer corrections on construction sites.

## 4.2 Technologies and their Potentials

Generally, two very different approaches are used to determine the position and orientation of the bucket: vision-based and non-vision-based technologies.

Non-vision-based technologies are mostly based on sensor applications. The sort of sensors is very diverse and linked to


Picture 2: Machine Control System with GPS sensors mounted on the excavator cab (picture taken at PORR, Sibiu)

their use. A case study on different sensors and their use in construction was published in May 2020. The results as presented in Table 1 [11] show that Link Motion technologies with Inertial Measurement Units (IMU) are most often used. They measure the absolute angle displacement and are dependent on each other, which makes calibration necessary. Their advantage compared to the cylinder length measurement technologies is an easy attachment and use in the excavator as well as the low price. [11] The critical part of these sensors is their susceptibility to errors due to vibration of the excavators, which indicates the need of an additional anti-vibration system.

The direct comparison of the IMU Link Motion measurement method and the draw-wire cylinder length show better results in error variance, reference trajectory and time delay for the draw-wire cylinder length measurement method. [11] This method uses a cable-actuated position or displacement transducer to measure the position, change in position and velocity of objects, in this case the cylinder length. [12] However, given the rough environment of construction sites, the laborious installation

Table 1. Sensor applications for guidance and control in excavators

| Cylinder Length | Link Motion | Revolute Joint | Hydraulic Parameters | Other |
|---|---|---|---|---|
| Magnetic (2x)<br>Stroke (3x)<br>Draw Wire (2x) | Inclination<br>Angle Sensor<br>Accelerometer<br>IMU (7x) | Rotary<br>Tilt<br>Potentiometer (3x)<br>Rotary Encoder | Hydraulic Motor<br>Pressure | RTLS<br>Vision |

Table 1: Sensor application for guidance and control in excavators (data based on [11])

and missing robustness of the wires represent the negative sides of this technology.[11]

Vision-based technologies can most often be used for multiple machines and machine interaction monitoring, while non-vision-based technologies are most often sensors, that are mounted on one machine or even on multiple parts of the machine. This illustrates the need for upgrading every machine, resulting in higher machine or installation costs and therefore lower accessibility to smaller companies. [13]

On the other hand, vision-based technologies are not machine-bound but location-bound. They can track multiple machines, because the overall field of view needs to cover all areas of possible construction work to create a seamless tracking possibility. The interviewed site managers question the efficiency of visual systems covering the whole construction site, as well as the feasibility of installing permanent cameras on a daily changing earthwork construction site. Even vision-based technology researches conclude that further “improvements should be geared toward integrating SRF (Simple Research Frameworks) with non-vision-based technologies” [14, p. 2351], because with video camera-based image processing, adverse weather and light conditions, overlapping of machines or suboptimal positioning of the camera may result in reduced quality or lack of necessary information and thus interrupt the real-time reliability of the system. [14]

Also, established technologies like GPS can be used. They are very popular for Machine Control, where GPS is used for position detection of the cab. (Pic.2)

Studies have shown that GPS-instrumented excavators show a higher accuracy and therefore “reduce the need to undertake finishing of the topography” [15, pp. 264–265], which comes along with reduced machinery usage time, significant fuel consumption reduction and limited risk of staff accidents. [15] An advanced technology called Infrared GPS (iGPS) from Metris Inc. was introduced for backhoe loaders to additionally determine the bucket position with multiple singe-point sensors on the linkage points. [16]

All these technologies have in common that they focus on the motion tracking to calculate the actual performance. But an equally important key demand on the way to represent the correct data is the replacement of estimations with measurements, in this case the estimation of the bucket volume. The first and so far only research that could be found addressing this topic, proposes the calculation of the weight inside the bucket. Successful implementation of these functions have been implemented in the Trimble LOADRITE systems. [17] [18] However, the invoice calculations for subcontractors (Fig. 1, 4.2-Calculations)

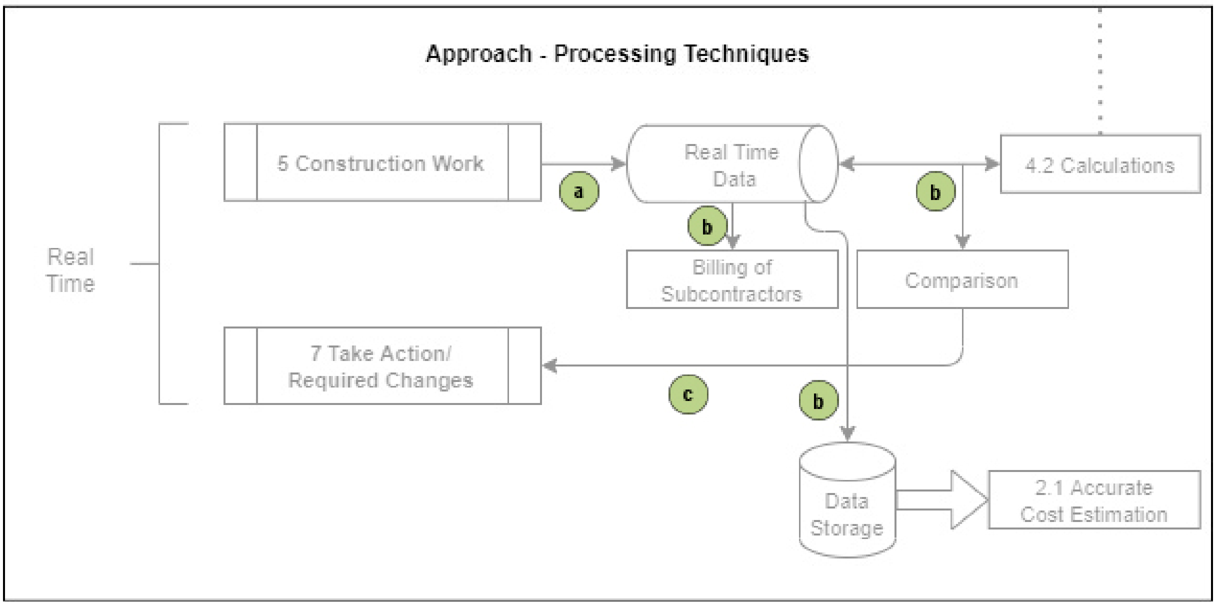


Figure 5: Approach Earthwork Construction Processing Techniques

and the whole planning of the Filling Processes (Fig.1, 1.2-Fill) are calculated in cubic meters which makes the determination of the bucket volume necessary and important. [19] The potential value of the exact volume inside an excavator bucket is described in Fig.4 as it saves the need and accordingly time and costs for changes.

### 4.3 Data Handling and Accessibility

Some additional requirements play an important role in the success of the approach. With the described technologies the required data can be extracted, however the "capability of handling this large volume of data in near real time" [14, p. 2342] is crucial to generate the actual productivity and make it accessible.

Accessibility is another important aspect. Looking at machine control for excavators - meaning the overview of real time information for the operator inside the machine - studies show an increased efficiency of 20-30% per machine. [20] Making this data available to everyone on construction sites, a significantly increased efficiency can be expected.

While a digital representation of the working machine is the first thing that comes to mind, the question is whether a full 3D visualization as described in [10, Ch. 4.5.2] is expedient in order to satisfy the formulated demands, or if a different data processing is necessary. Jobsite Management software addresses this problem to prevent unused valuable data and limited visibility of the data. Information on all machines is centralized, machine quality, performance as well as diagnostics generated and then made accessible to managers and contractors on a variety of devices. [21]

RFID tracking (Radio-Frequency Identification) has, in the past, mostly been used for tracking the earthmoving through truck movements on a bigger scale. Passive RFID tags have been mounted on trucks and the readers were placed on the dump areas. [8]

Further research is necessary to test an approach for RFID truck-excavator recognition, which could be used for spatial relationship capturing of the excavator

Picture 3: Truck line up for excavator filling (picture taken at PORR, Sibiu)

bucket tip and the truck loading area. With the unique identification of excavator and trucks a higher coherence of earthmoving tracking could be created. [22] This could be especially interesting and useful, the more information about the earth quality has been collected in previous steps of the process.

There are existing AI solutions for material classifications in earthwork construction. Further research would be necessary to see if these solutions can be integrated in the bucket sensor system. [23] According to the interviewed site and operational managers the traceability of the earth from excavation to filling, including material and quality classification, would have a huge potential in terms of warranty management and sustainability.

To summarize, Fig.5 focusses on the processing techniques of the approach shown in Fig.4 and contains three major steps. (a) First, available technologies need to be examined to test their efficiency of reliable and accurate extraction of the needed data. (b) Second, technology with the capability of "handling this large volume of data in real time" [14, p. 2342] and (c) third, software for an appropriate representation, processing and visualization of the data to make it accessible and usable for all parties that could profit from this information source.

## 5. Conclusion and Outlook

Infrastructure industry is rising and "the pressure is on contractors to deliver value to the project owner through increased project safety, budget and scheduling compliance." [21] The huge impact that construction machinery has on the whole process of earthwork constructions is indisputable. [14] Machine control is a first step to address these challenges, it is constantly measuring valuable data. However, the full potential of collecting or using this data is yet to be unlocked. [21]

Contractors sometimes fear that collecting data on an operating machine sacrifices time delays and reduced productivity of this machine to add value to the whole construction chain. The comparison of machines without sensors and with sensors give proof that the work of the excavator intrinsically profits from extracting information to a bigger system. [20] Studies show a 22.93%- time reduction associated with less working hours, lower running costs and waiting time reduction of up to 80%. [20] (Pic.3)

The industry has a high demand of upgraded machinery [1] and many different technologies are used for different purposes around the field of excavator tracking. Most of them concentrate on one specific purpose. Examples are quantifying the idle time [24], monitoring the utilization and abnormal production scenarios [14] or measuring the fuel consumption or running time. [25] [11]

Opportunities in the future need to focus on the whole earthwork construction chain and determine suitable technologies according to the adaptability of the overall strategy and workflow to thus improve the whole process.

This paper reflects the current workflow and the importance of extracted real-time machine data within this workflow for billing, productivity monitoring, progress visualization and future estimations. It points out the need of higher data accuracy. Furthermore, it is established that estimations for calculation purposes are insufficient and lead to higher cost deviations during construction.

“Nearly 2/3 of contractors say that being able to gather accurate data from the field contributes most to their ability to improve performance.” [26] Most important for them are, in order, Project Performance Data, Payroll, Productivity Data, Safety Data and Equipment Tracking Data. [26] As this paper shows, the correct tracking of excavator activities can contribute to all these criteria. Benefits reach from an improved ability to win a contract, increased safety, greater profitability and productivity to - last but most important - a better ability to complete projects on or under schedule and budget. [26]

## 6. Acknowledgements

Gaining insight and experience on an earthwork construction site have been crucial parts in writing this paper, its ideas and approaches. Therefore, I would like to thank PORR AG for providing me the opportunity to inspect the new technologies as well as the daily challenges that arise on site.

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