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**Authors**
Fischer, Anne
Grimm, Niklas
Tommelein, Iris D.
et al.

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# VARIETY IN VARIABILITY IN HEAVY CIVIL ENGINEERING

**Anne Fischer[1], Niklas Grimm[2], Iris D. Tommelein[3], Stephan Kessler[4], and Johannes Fottner[5]**

## ABSTRACT

This paper presents a characterization of heavy civil engineering in the context of lean construction and Industry 4.0. Production characteristics of earthworks are compared with those of multi-story construction. The paper focuses on the equipment use of specialty foundation contractors and shows the variety in variability encountered in the Kelly pile drilling process, as described by industry experts. The authors identify seven sources of variability that affect production performance, classify each one by type, and then describe technologies to harness them. The paper critically examines design considerations in a production system that highly depends on equipment and highlights that advances in implementation of Industry 4.0 will demand ongoing effort in reconfiguring such systems.

## KEYWORDS

Lean construction, earthwork, heavy civil engineering, process, value stream, variability.

## INTRODUCTION

Industry 4.0 envisioned as Germany's high-tech strategy plan for 2020 and characterized by digitalized production optimized using artificial intelligence (AI) (Lasi et al. 2014), challenges the construction industry to adopt digital technologies in order to address its ever-increasing complexity (McKinsey 2017). However, industry digitalization and optimization is slow due to construction-specific constraints (e.g., Günthner and Borrmann 2011, Schöberl et al. 2020) such as diverse use of technologies in stand-alone applications (lacking interoperability), variety of proprietary platforms, lack of uniform interfaces for documentation and coordination, and lack of digital mapping of processes. A key lesson from lean production is that a pure adaptation of technologies does not optimize a process (Lander and Liker 2007). Rather, process flows must be understood

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[1] PhD Student, Chair of Materials Handling, Material Flow, Logistics, Dept. of Mech. Engrg., Techn. Univ. of Munich, Germany, +49 89 289 15932, anne.fischer@tum.de, orcid.org/0000-0002-2106-3735

[2] Graduate Student, Chair of Materials Handling, Material Flow, Logistics, Dept. of Mech. Engrg., Techn. Univ. of Munich, Germany, niklas.grimm@tum.de, orcid.org/0000-0002-4798-6028

[3] Professor, Civil and Envir. Engrg. Dept., Director, Project Production Systems Laboratory (P2SL), University of California, Berkeley, CA 94720-1712, USA, +1 510 643-8678, tommelein@berkeley.edu, orcid.org/0000-0002-9941-6596

[4] Academic Director, Chair of Materials Handling, Material Flow, Logistics, Dept. of Mech. Engrg., Techn. Univ. of Munich, Germany, +49 89 289 15925, stephan.kessler@tum.de , orcid.org/0000-0001-7330-0790

[5] Professor, Chair of Materials Handling, Material Flow, Logistics, Dept. of Mech. Engrg., Techn. Univ. of Munich, Germany, +49 89 289 15918, j.fottner@tum.de, orcid.org/0000-0001-6392-0371

in detail to eliminate waste (Rother and Shook 2009). So, while equipment-driven operations have been designed around optimization of equipment use, and the cost of equipment outweighs other costs in their operation, factors other than equipment cost minimization play a role in overall process optimization.

This paper focuses on pile drilling, a heavy equipment-intensive application. The Kelly drilling method, widely-used for pile production, uses a rotary drilling rig ("rig" in short) to make large-diameter bored piles up to 3 m (DIN EN 1536) (Figure 1). This method repeatedly drills and removes soil. Other methods for pile production exist, e.g., the Continuous Flight Auger (CFA) method (Brown 2004, 2005). CFA production is optimized for continuous movement of soil and concrete: soil is transported upward via the auger and concrete is transported downward via a hollow core inside the auger. Unlike the Kelly method, CFA does not have the same range of application in pile design so one is not an exact substitute for the other.

Figure 1: Rotary drilling rig at test site of Bauer Group in Schrobenhausen, Germany (Pictures by Fischer, A.)

Noting that few documents describe the Kelly pile production process and its variabilities, the authors posed three research questions: *What are key differences between (foundation) civil engineering and multi-story building construction in terms of application of lean principles? Which variabilities influence the Kelly drilling production? How may these be addressed by Industry 4.0?*

## RESEARCH METHOD

To answer these questions, the authors conducted semi-structured interviews with nine experts from three German specialty foundation contractors involved in the different construction phases: Two estimators, one purchasing agent, two equipment schedulers, two construction managers, and two foremen. The experts were asked to describe their method for producing a Kelly pile in the design-, project preparation-, and execution phase. To supplement this knowledge, Grimm (2020) (a co-author of this paper) searched the literature to identify means of estimating production rates of earthmoving and pile driving operations the research questions.

## RELATED WORK

### CHARACTERISTICS OF MULTI-STORY AND HEAVY CIVIL CONSTRUCTION

Variability in construction results from variation within and between process interactions (Howell et al. 1993). Process interactions may depend on shared resources, such as cranes in multi-story construction. Cranes are pacemakers, largely responsible for material flow, and used by many stakeholders on-site (Tommelein and Beeche 2001, Friblick et al. 2009, Dallasega et al. 2015). Monitoring crane operations is therefore important when trying to design work standards to reduce variability (Fazinga et al. 2016). When comparing multi-story construction with heavy civil engineering, a key difference is that the latter deals as much with the sharing of resources as it does with the interdependence between them.

Differences pertain to characteristics of in-situ production, the number of different task types, the number of subcontractors working concurrently, and work space requirements depending on the equipment. As part of heavy civil engineering, earthworks are widely discussed in the literature. For example, Kirchbach et al. (2014) describe earthwork production composed of the following material flow: material excavation and loading by excavators, material transportation by trucks, and spreading with bulldozers, where the (cost) deciding factor is the process involving the excavator. To measure production flow, Haronian and Sacks (2020a, 2020b) distinguish between discrete elements (building construction) and layered elements (earth movement). Kalsaas (2012) adapts Overall Equipment Efficiency (OEE) as a metric but emphasizes the need to consider the entire production system, i.e., isolated consideration of the equipment is not sufficient. The importance of the worker, even in equipment-intensive work is shown by the work of Ruiz et al. (2020), whose implementation of 5S led to a demonstrable improvement in working conditions. Kirchbach et al. (2012) confirm that civil engineering, in particular earthmoving, is strongly characterized by uncertainties.

Pile production is known for its dependence on variable and difficult-to-predict geology (Kaplan et al. 2005). However, Rosas et al. (2011) reveals that even though planners complain about the geology's variability, planning mistakes have an even greater effects on forecasts. González et al. (2014) look at geothermal drilling, which, like bored pile production, is characterized by complex processes carried out by highly specialized trades. Established contractual and organizational structures, based on mutual distrust and secrecy, reduce project performance. In contrast to earthmoving, the pile as a product can be seen as a single object, similar to building construction. If one considers the equipment, the rotary drilling rig is less flexible in use compared to the hydraulic excavator. In the following, we investigate the soundness of the common assumption that equipment drive production flow, i.e., that the system is 'paced by equipment' (Haronian and Sacks 2020b).

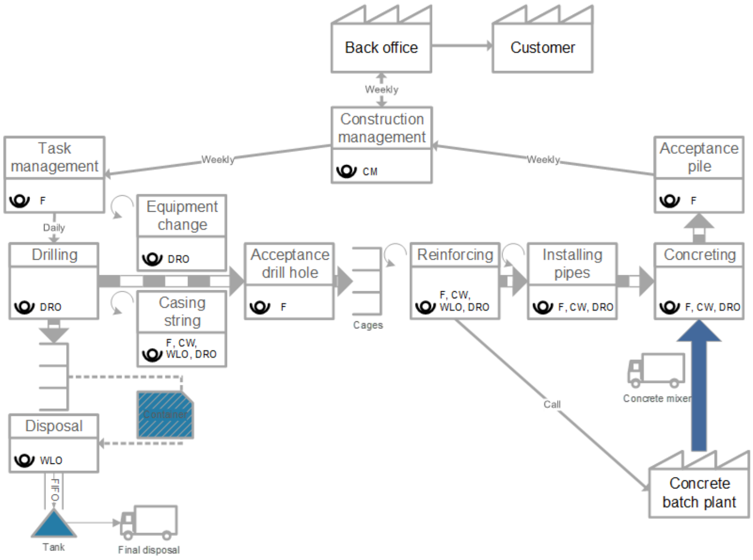
### CHARACTERISTICS OF VARIABILITY IN PRODUCT AND PROCESS

Different approaches exist to deal with all this variability. Tommelein (2000) argues that these models are useless if they are not able to address both, the product as well as the process variability in a production system. More specifically, one needs to define sources of variability in a system to identify the adjustments that can be made in order to manage or even improve the system. The product is defined by its parts whereas the process is defined by its activities (Filho et al. 2016, Tommelein 2000). Examples of product characteristics concern, e.g., functionality, configuration, and geometry. Process characteristics concern, e.g., resource assignment and sequencing of activities.

## PILE PRODUCTION USING KELLY DRILLING METHOD

The key metric in pile production is the output of pile length produced per day (or piles per day). Based on this value, the number of units of equipment and accessories, such as casing oscillators, is determined based on experience.

Pile production using the Kelly drilling method consists of three main steps: drilling, reinforcing, and concreting, as detailed next. Figure 2 depicts a value stream map of the whole process.



CM: Construction Manager
F: Foreman
CW: Construction Worker
DRO: Drilling Rig Operator
WLO Wheel Loader Operator

Figure 2: Value stream map for pile production using Kelly drilling method

Once the rig has been positioned, the alternating steps of the drilling process start. The equipment picks up the appropriate tool, e.g., an auger (Figure 1 left). The equipment slews and positions itself towards the drilling attachment point. The rotary drive turns in the casing string with the help of the casing drive adapter (Figure 1 right). Lowered with the help of the telescopic Kelly bar, the drilling tool drills as the rotary drive applies the torque on the locked Kelly. Once filled, the drilling tool is pulled out and emptied, usually in a container to ease soil removal from site. In turn, a wheel loader then takes the drill cuttings to the disposal site for further processing. In general, the deeper the drilling tool, the lower the performance due to longer run-in/out times and higher surface friction. For reinforcement, the rebar cage is attached to the auxiliary cable of the rig and setup. The rig then swivels to the drilling attachment point to lower the reinforcement cage. Before concreting starts, the delivery pipes are assembled and lowered into the drill hole. The workers fasten them together. Concrete is placed either directly through the concrete mixer discharge or through a concrete pump/bucket, which requires additional steps. Cutting the casing and delivery pipes is done alternately and often requires extra power from a casing oscillator. The quality of the material is highly dependent on the correct execution (Brown 2004).

## SOURCES OF VARIABILITY

The expert interviews and the literature revealed 7 sources of variability.

**(1)** The design, tied directly to the method and use of resources, depends greatly on the **contractual requirements**. A collaborative partnership is rare between designers, material supplier, and foundation contractors. In the design phase, early involvement of the specialty foundation contractors minimizes the product variability as they may aim to standardize, i.e., length, inclination, and diameter of the piles. All these influence the equipment selection, the auxiliary equipment (casing oscillator), the procedure, and the performance (the longer the pile, the higher the casing friction, the longer the excavations).

Rebar joints should be minimized, if possible, as they entail additional work steps. Specialty foundation contractors work together with material suppliers. Considering the rebar, the delivery and storage of the cages must be in the right sequence (process). Transportation restrictions limit the pile length (product). While concrete contractors are under subcontract to the specialty foundation contractors, in practice, concrete supply will vary. The more flexibly concrete can be called off and the more reliable the transportation is, the better the production flow and the utilization of the rotary drilling rig, but also the quality of the product. In general, increased requirements on the product design characteristics and quality, such as inclined boreholes or floating foundations, determine further process steps, e.g., at which point the inclination needs to be checked.

**(2)** Variability in the process stems from **environmental influences**, e.g., weather and time, and affect site processes in different ways. Poor conditions can reduce performance by as much as 50-70 % (Girmscheid 2010, Hoffmann and Krause 2016). While the drilling process is stationary, the rig must travel between pile locations. Poor visibility or slippery conditions have less influence on the performance of the drilling than is the case for earthmoving equipment. However, inclement weather conditions, such as strong winds or heavy rain, are unfavorable to the mast’s inclination or the equipment foundation's stability. In addition, the work of construction workers is affected by inclement weather, seasonally and daily (e.g., night time construction).

**(3)** Environmental influences can be managed by good **site organization** planned in advance. An important part of the site organization is to ensure good time management to achieve high equipment utilization. The time utilization factor provides information on how well the working time is utilized. Reducing factors such as a 50-minute hours (83%) (Bauer 2007, König 2014) are commonly used in special foundation engineering. The influence of site organization is difficult to capture analytically but pertains to factors such as the organization and scope of work, as well as interruptions, maintenance, and repair (Hoffmann and Krause 2016). In special foundation engineering, examples for a good site organization are the provision of spare parts, additional equipment, like casing oscillators, mechanics, buffer time, tight coordination with the concrete supplier.

**(4)** The **geology** has an enormous influence on the product and process variability. First, the chosen pile design and procedure is based on the soil type. Second, considering the equipment performance, the soil type is included in the theoretical production rate as the volume depends not only on the rated volume but also on the load factor, defined by the fill factor and the swell factor of the material (ISO 1991). In special foundation engineering, the depths of the layer boundaries in the area of the bored piles are based on individual test borings. Practical experience shows that soil layer models give only a very limited prediction of the material present. Moreover, boulders lead to inhomogeneity and disturb the sequence up to a complete standstill. Groundwater also plays a role. The optimum filling level of the tool, as well as the selection of the tool, depend on the soil condition (but also on the operator's skills). Equipment sensor systems help.

**(5)** A frequently-mentioned process indicator is the equipment operator’s **skills**. Depending on the operator, pile production rate is very high or very low. According to Girmscheid (2010), a novice may reduce it by up to 20-35 %. Experts in special foundation engineering confirm this and back it up with estimates of performance increases of up to 20 % if above-average operators are deployed (independent from existing operator assistance systems). These are decisive for the process. Changing over rotary drilling tools is also complicated and requires a high level of experience. Careful handling of the equipment, such as occasional cleaning of the chains, also helps reduce downtime. Rashidi et al. (2014) cite another factor regarding personnel in the case of bulldozers, the number of consecutive working days. This is also confirmed in special foundation engineering. Experts speak of approximately one week to create a team, and the more well-rehearsed the team is, the greater their performance will be.

**(6)** Improving the **operating conditions** can help to reduce process variability. Some operating conditions in heavy civil engineering are similar, such as manoeuvrability, or the geodetic height of the construction site. Differences occur considering the distance between the start and endpoints of the load cycle. E.g., targeted loading reduces the production rate up to 10 % (Bauer 2007). In the case of dozers, working in tracks increases it up to 20 % (Girmscheid 2010). In the case of rotary drilling rigs, the distance between the drill holes plays a role as well since with longer distance the pure share of drilling in the working time is reduced.

**(7)** The degree of **abrasion and failure** must be quantified. Girmscheid (2010) provides an increase up to 80 % for hydraulic excavators. In the case of rotary drilling rigs, the abrasion of tools, such as auger teeth or casing shoes, must be accounted for. In particular, casing shoes have a significant impact on the performance as they remain underground until concreting. Premature abrasion delays reaching the required drilling depth. In softer soils, such as clay, abrasion plays a minor role. The probability of failure of hydraulic excavators during long-term operation is a function of their operating hours (Girmscheid 2010) but the impact of failure is lessoned by preventive maintenance. In the case of rotary drilling rigs, preventive maintenance is all the more important as acquisition and maintenance costs are much higher than for hydraulic excavators.

## INDUSTRY 4.0 TOOLS TO ADDRESS VARIABILITY

Industry 4.0 offers opportunities to reduce the seven sources of variability, as described, by providing smart technologies (Oesterreich and Teuteberg 2016, Huang et al. 2021):

**Digital models:** Building Information Modeling (BIM) provides a digital representation of the construction project (ISO 2018). While widely used in building construction, BIM is not used in heavy civil engineering (Fosse et al. 2016). Instead, Geographic Information System (GIS) may be used to capture the geospatial context of infrastructure systems. The software capabilities of BIM and GIS are increasingly overlapping (Liu et al. 2017). A German initiative is pushing for standardization in special foundation engineering (Germ. Constr. Ind. Fed. 2019).

**Internet of Things (IoT):** With the help of sensing (e.g., RFID and Bluetooth), entities on site, such as workers, material, and equipment, are connected via the Internet for identification, localization, and performance tracking (Olivieri et al. 2017).

**Artificial Intelligence (AI):** Machine learning algorithms are used to analyze the increasing flood of data. Ongoing research aims at automatically capturing construction progress (e.g., Bügler et al. 2017, Fischer et al. 2021a).

**Simulation:** Simulation is a proven tool for testing complex systems and is a key tool for virtual design and construction, albeit not yet widely used in construction practice (AbouRizk 2010, Abdelmegid et al. 2020). Recent approaches address opportunities provided by frequent updates of construction site data (e.g., Louis and Dunston 2017, Akhavian and Behzadan 2018, Fischer et al. 2020, Fischer et al. 2021b).

Table 1 describes how each variability can be harnessed by these technologies.

Table 1: Variabilities in relation to Industry 4.0 tools

| | Variability | Digital model | IoT | AI | Simu-lation | Appropriate technologies help… |
|---|---|---|---|---|---|---|
| (1) | Contractual requirements | x | | | x | gain a better understanding by visualization. |
| (2) | Environmental influences | | | x | x | handle weather forecasts. |
| (3) | Site organization | x | x | | x | visualize and test site logistics in advance. |
| (4) | Geology | x | | x | x | visualize the single soil layers to improve reaction time. |
| (5) | Operator skill | | x | x | x | track and analyze personnel's performances. |
| (6) | Operating conditions | | x | | x | monitor and virtually test routing strategies. |
| (7) | Abrasion and failure | | | x | x | predictive maintenance and capture stochastic failure. |

## DISCUSSION

Use of Industry 4.0 technologies to reduce variability can help make systems more predictable. Not all variability will be removable, but incrementally the production system will evolve to new future states, each with new system design challenges to be overcome. As the interviews revealed a high degree of human processes on construction sites, a pre- or co-requisite to introducing Industry 4.0 tools, is improving contractual and organizational aspects by using lean management tools. Whereas the multi-story buildings are characterized by the use of cranes challenging the decoupling of different tasks, the earthworks focus is on fleet interaction. In contrast, the foundation-pile activities have been isolated and limited as a one-piece flow line dependent on single machine due to high complexity. The comparison of the application of lean principles, however, shows that even equipment-intensive processes can be improved by focusing the human factors. Transferred, collaborative partnerships involving contractors at an early stage can improve the pile design towards production aspects.

## CONCLUSIONS

Special foundation engineering is a competitive field, driven by product and process knowledge. Focusing on the Kelly drilling process in this paper, it was therefore not surprising to not find literature on influencing factors. A comparison with conventional methods in earthmoving and interviews with experts reveal seven sources of variability and derived recommendations. More interviews and additional data collection are in order to lead to more general conclusions, however, this study indicates that process improvements will depend not solely on equipment improvements with Industry 4.0 but on improvements in the socio-technical system as a whole, to fully account for individual people and organizational factors as well. Implementation of lean principles within and between parties can help capture the variability. Standard workflows then serve as a basis for adaptive simulation studies.

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