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Comparative assessment of deterministic methodologies for estimating excavation productivity

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Abstract: This paper investigates the prediction capability of deterministic methodologies in estimating construction productivity for earthmoving operations. Published literature includes several estimation methodologies stemming from (a) equipment manufacturers' manuals, (b) editions from German contractors' associations or individual researchers and (c) textbook editions. The purpose of this research is to assess the yielded productivity estimation results under the prism of 14 estimation methodologies. It is – to the authors' best knowledge – the first research attempt for the comparative evaluation of such a diverse set of estimation methodologies, with the aim of quantifying their effects on the operations analysis in earthmoving works. A uniform mathematical modelling approach is used to formulate the relevant estimation equations and, subsequently, a real-case scenario of an earthmoving project in Greece is used as a benchmark against which the robustness of each methodology is assessed. A sensitivity analysis on main productivity factors concludes the research. The preliminary results indicate that equipment manufacturers' methods are more optimistic and present higher sensitivity to specific productivity factors (e.g. swing angle, excavation depth), whereas the German-oriented approaches are more conservative with less variability due to differing productivity factors.

Keywords: construction productivity, estimation, excavation, statistical analysis

1 Introduction

Although many firms attempt new technologies or apply scientific methodologies, the cost and duration of construction activities (both equipment- as well as labour-intensive) depend on the expected output per time unit, which is usually termed 'production rate' or 'productivity' (Park et al. 2005). Alternatively, productivity is defined as 'Output/Input' or 'Production/Resource', where resources may be plant or even labour crews (AbouRizk et al. 2001; Cottrell 2006; Panas and Pantouvakis 2010a). Within the framework of the present research, the term 'productivity' represents the production rate at the activity level of a construction project. Managerial decisions taken by construction operatives, as well as the dynamically changing operational conditions, which reflect the project's nature, influence heavily the achieved productivity on-site (Chaudari et al. 2022). All these parameters have to be taken into account prior to the commencement of the works, in order to determine the work method and construction technique, as well as improve operational efficiency (Kotte 1997). Regardless of which productivity estimation methodology is finally adopted, it is very important to include the operational factors' variability in the analysis (Peurifoy and Schexnayder 2002). Therefore, robust productivity assessment depends on the extent up to which the estimator has knowledge of (a) the key operational factors that affect productivity, (b) the extent of their variability, (c) their effect on the outputs of the selected productivity methodology and (d) the best suited methodology for analysing the particular construction scenario per se.

The exact effect of operational factors on productivity is not just a matter of comparing the output of different productivity estimation methodologies (Panas and Pantouvakis 2010a), but rather depends on examining a specific construction case under the prism of the variability in the estimation approaches (Panas and Pantouvakis 2010b; Panas and Pantouvakis 2015). This paper's contribution to

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the aforementioned research problem is expressed through the compilation of a thorough analysis of 14 productivity estimation methodologies stemming from (a) equipment manufacturers' manuals, (b) editions from contractors' associations or individual researchers and (c) textbook editions. It is – to the authors' best knowledge – the first research attempt for the comparative evaluation of such a diverse set of estimation methodologies, with the aim of quantifying their effects on the operations analysis of construction activities. In essence, the study's objective is the formulation of a comparative framework that will demonstrate the variability range in productivity estimates under the influence of different operational conditions that affect construction activities. In other words, the research serves as a benchmark against which an estimator or professional engineer may test the sensitivity of different estimation methodologies, that are directly applicable in different projects, regardless of the particular characteristics of each country or construction industry per se. Due to the diverse nature of the methodologies' potential applications, the paper's focus is limited to the execution of the excavation works, since they constitute a relatively straightforward implementation framework for implementing equipment-oriented productivity estimation methodologies (Bai et al. 2019; Chen et al. 2021; Kassem et al. 2021).

The structure of the paper is as follows: First, a short presentation of the selected productivity estimation methodologies is presented in the next section. Subsequently, the main theoretical concepts of the fourteen estimation methodologies are presented, in order to compare their input requirements and respective outputs. The analysis is enhanced with a qualitative and quantitative evaluation of all research variables, with a particular focus on the presented productivity factors. Then, the research methodology is going to be delineated, followed by a concise description of an excavation case study. The yielded results are going to be presented and, subsequently, a sensitivity analysis is conducted on two critical productivity factors, namely the digging depth and the swing angle from the digging position to the dumping location. Finally, the study's main inferences are described and the formulation of future research directions concludes the study.

2 Background

2.1 Theoretical concepts of productivity estimation methodologies

Construction productivity can be either assessed by the application of data-oriented methodologies (e.g. statistical regression models, artificial neural networks), when measurements from similar past operations are available, or by implementing process oriented methodologies, when no historical data are available or applicable (Zayed and Halpin 2004). The latter is often the case, especially when innovative construction techniques are applied or new equipment is deployed for a specific construction activity. Such generic, process-oriented methodologies have been published in equipment manufacturers' manuals (Liebherr 2003; Komatsu 2013; Volvo 2015; Caterpillar 2016), editions from contractors' associations or individual researchers in Germany (Garbotz 1966; BML 1983; Kühn 1984; Kotte 1997; Hüster 2005; Hoffmann 2006; Bauer 2007; Girmscheidt 2010) and textbook editions (Peurifoy and Schexnayder 2002; Nunnally 2007). It should be noted that published research that is loosely based or derived from the aforementioned publications has been excluded from the study for brevity reasons (e.g. Edwards and Holt 2000).

Furthermore, as the main research objective is the comparative evaluation of the published estimation methodologies, the present research does not scrutinise the available analytical techniques except from the deterministic approach that serves the research purpose: the evaluation of different productivity factors for the estimation of construction productivity. In other words, although similar analyses may be conducted under the prism of alternative modelling techniques, such as queueing theory (Carmichael et al. 2014; Sheikh et al. 2016; Carmichael and Mustaffa 2018) or even simulation (Pantouvakis and Panas 2013), this research is limited to the direct application of each estimation methodology's deterministic mathematical formula and the use of statistical analysis for the comparative evaluation of their results. This rationale is corroborated by the fact that, as of today, estimating engineers find it is easier to understand and relate to physical features, defined as first-order factors, since in the deterministic models the parameters that define productivity are stated in physical terms (Schexnayder 1997).

The estimation of construction productivity for this research is based on the theoretical assumptions of the factor model (Thomas and Yiakoumis 1987), which distinguished between the theoretical (Q_{th}) and the effective productivity (Q_{eff}). The former represents the best possible productivity rate under ideal operational conditions, while the latter adjusts theoretical productivity under the influence of the actual on-site working conditions. In excavation operations, the mathematical model that converts Q_{th} to Q_{eff} takes into account a series of multipliers that represent the so-called productivity factors, as summarised below (Panas and Pantouvakis 2015):

$$Q_{eff} = Q_{th} * \prod f = \left(\frac{V_{SAE/CECE}}{t_c} \right) * f_s * f_{fill} * f_E * f_{skill} * f_{avail} * f_{swing}$$
$$* f_s \left({}^{1}\!/_{f_{depth}} \right) * f_{swing-depth} * f_{dump} * f_{vol} * f_{wear} * f_{alt} *$$

where (in order of appearance) Q_{eff} indicates the effective excavation productivity (m^3/h), Q_{th} the theoretical excavation productivity (m^3/h), Πf the productivity factors that are diversified according to the applied estimation methodology, $V_{SAE/CECE}$ the rated bucket capacity (m^3), t_c the cycle time, f_s the swell factor (–), f_{fill} the bucket fill factor (–), f_E the job efficiency factor (–), f_{skill} the operator skill factor (–), f_{avail} the equipment availability factor (–), f_{swing} the swing angle factor (–), f_{depth} the excavation depth factor (–), $f_{swing\text{-}depth}$ the combined swing angle and digging depth factor (–), f_{dump} the bucket dump factor (–), f_{vol} the excavator-truck volumes match factor (–), f_{wear} the bucket teeth wear factor (–) and f_{alt} the altitude factor (–).

Each of the aforementioned factors is related to one or more estimation methodologies. It should be noted that even when a specific factor is common between two or more estimation methodologies, their values' range may differ, thus creating even more variability in the yielded results, as will be practically demonstrated in the following paragraph.

2.2 Comparative analysis of excavator productivity factors

The main productivity factors that are used in the mathematical expression for the estimation of excavation productivity are explained below:

- **Rated bucket capacity ($V_{SAE/CECE}$ in cubic metres):** The so-called nominal heaped bucket capacity is specified according to international standards. The German-oriented methodologies usually apply the CECE (1973) standard (V_{CECE} with angle of repose 1:1), while all other methodologies apply the most commonly used SAE (1993) standard (V_{SAE} with angle of repose 1:2). The rule of thumb is that $V_{SAE} \approx (1.15–1.20) \star V_{CECE}$;
- **Cycle time (t_c in seconds):** The cycle time is given a specific values' range according to specific criteria set by each estimation methodology: swing angle (Komatsu 2013), model type and working conditions (Peurifoy and Schexnayder 2002; Liebherr 2003; Caterpillar 2016), soil type and working conditions (Volvo 2015), and soil type and bucket capacity (BML 1983; Hüster 2005; Nunnally 2007). The latter is applied for all other German-oriented estimation methodologies;
- **Swell factor (f_s):** It depends on the soil type and expresses the quotient of the bank volume unit weight (in its natural position) to the loose volume unit weight after excavation. Equipment manufacturers' manuals (e.g. Catepillar 2016) usually provide indicative values in respective tables, while German-oriented methodologies are based on the DIN18300:2012 soil classification system to associate each soil category with indicative f_s values;
- **Bucket fill factor (f_{fill}):** It expresses the actual load volume in the excavator's bucket in relation to its rated capacity, taking into account the soil characteristics. For cohesive soil (e.g. clay) $f_{fill} > 1$, while for rocky material $f_{fill} < 1$, since there are large voids left in the bucket. The German-oriented methodologies follow again the DIN 18300:2012 standard, while equipment manufacturers (Liebherr 2003; Komatsu 2013; Catepillar 2016), as well as Nunnally (2007), provide indicative values based on specific criteria (e.g. soil type and excavability, equipment type). Peurifoy and Schexnayder (2002) adopt the approach of Caterpillar (2016);
- **Job efficiency factor (f_E):** It expresses the variation in productivity due to delays in the working cycle (e.g. delays or work breaks, unforeseen stoppages). It is calculated as $f_E = (60 - \Sigma[\text{delays in min}])/60$. It normally ranges between 0.75 and 0.85;
- **Operator skill factor (f_{skill}):** It expresses the effect of the operator's skill and experience on productivity. A qualitative scaling of the operator's skill is specified in either three (Caterpillar 2016) or four categories (Kotte 1997; Liebherr 2003) (e.g. Very good, Good, Average and Amateur). It is interesting that Kühn (1984) also associates the psychological and physical condition of the operator to derive respective skill values that range in the area of 0.45–1.10;
- **Equipment availability factor (f_{avail}):** It expresses the decrease in productivity due to unforeseen breakdowns of the equipment (Volvo 2015). The values' range is 0.65–1.00 (Kotte 1997) with the most probable value being ~0.80 (Hüster 2005);
- **Swing angle factor (f_{swing}):** It expresses the variation of productivity due to the boom's swing angle from the excavation face to the dumping position. The smaller the swing angle, the more productive the equipment, with optimum productivity lying in the range 30°–60° (BML 1983). The rule of thumb is: for angles >90°, $f_{swing} < 1$, while for angles <90°, $f_{swing} > 1$;
- **Excavation depth factor (f_{depth}):** It expresses the variation of productivity due to the depth from the excavator's position to the excavation ground.

The German-oriented methodologies associate f_{depth} with the soil categories, with f_{depth} having its maximum value (f_{depth} = 1) for excavation depth equal to 1 m and then gradually decreasing for depths up to 7–8 m. The equipment manufacturers (Komatsu 2013), on the other hand, define specific job conditions for which the cycle time should be adjusted. It is implied that the average values of the cycle time correspond to an excavation depth equal to 50% of the machine's maximum capability and then it should be accordingly increased or decreased for worse or better job conditions;

- **Combined swing angle and digging depth factor ($f_{swing\text{-}depth}$):** This factor is defined by Peurifoy and Schexnayder (2002), as well as Nunnally (2007). The former provide values that associate the quotient (%) of the excavation depth (h_{exc}) to the maximum excavation depth (h_{max}) with the swing angle (45°–180°), while the latter use the same rationale with the distinguishing point being the fact that they take into account the maximum excavation depth instead of the optimum. The values' range is 0.62–1.33;
- **Bucket dump factor (f_{dump}):** It expresses the variation of productivity due to the applied dumping method (e.g. free or targeted dump). The German-oriented methodologies set maximum f_{dump} = 1.0 for free dump and reach to a minimum of f_{dump} = 0.58 for dumping soil in a storage silo;
- **Excavator-truck volumes match factor (f_{vol}):** This factor is used by the German-oriented methodologies and refers to the combinatory excavator-truck system. It reflects the need for increased manoeuvring in case there is a large bucket unloading on a relatively small truck (BML 1983). For $V_{truck}/V_{exc} \geq 10\text{–}11$, then $f_{vol} \approx 1.0$;
- **Bucket teeth wear factor (f_{wear}):** It expresses the decrease in productivity due to bucket teeth wear (Kotte 1997). The approach is also adopted by other German-oriented methodologies (Garbotz 1966; Bauer 2007; Girmscheidt 2010), for new (f_{wear} = 1.0), medium-used (f_{wear} = 0.90) and worn (f_{wear} = 0.80) teeth;
- **Altitude factor (f_{alt}):** This factor has been set by Garbotz (1966) and Kotte (1997) in the sense that the higher the altitude, the less the performance of the equipment's engine. For up to 500 m, the altitude values of f_{alt} are close to 1.0.

Each estimation methodology combines part of the aforementioned factors, in order to yield estimates of construction productivity, as shown in Table 1 below. This research adopts the deterministic analysis, which is based on analytical mathematical models that produce single-value estimates. Despite the crude simplification of reality in relation to other modelling techniques (e.g. stochastic or statistical), the deterministic approach remains popular between construction operatives since it captures the physical meaning of the operational factors in the calculations. In that view, the main research question is formulated as follows: How do different estimation methodologies incorporate the aforementioned productivity factors in their calculations and what is the extent of their variability? This issue is discussed in the following sections.

Tab. 1: Comparative evaluation of productivity estimation methodologies' factors.

No.	Estimation methodology	Productivity factors
1	Bauer (2007)	f_s, f_{fill}, f_{swing}, f_{depth}, f_{dump}, f_{vol}, f_{wear}, f_E
2	BML (1983)	f_s, f_{fill}, f_{swing}, f_{depth}, f_{dump}, f_{vol}, f_E
3	Caterpillar (2016)	f_s, f_{fill}, f_{skill}, f_E
4	Volvo (2015)	f_s, f_{fill}, f_{avail}, f_E
5	Garbotz (1966)	f_s, f_{fill}, f_{swing}, f_{depth}, f_{dump}, f_{vol}, f_{wear}, f_{alt}, f_{avail}, f_{skill}, f_E
6	Girmscheidt (2010)	f_s, f_{fill}, f_{swing}, f_{depth}, f_{vol}, f_{wear}, f_{avail}, f_{skill}, f_E
7	Hoffmann (2006)	f_s, f_{fill}, f_{swing}, f_{depth}, f_{dump}, f_{vol}, f_E
8	Hüster (2005)	f_s, f_{fill}, f_{swing}, f_{depth}, f_{dump}, f_{avail}, f_{skill}, f_{vol}, f_E
9	Komatsu (2013)	f_s, f_{fill}, f_{depth}, f_E
10	Kotte (1997)	f_s, f_{fill}, f_{swing}, f_{depth}, f_{dump}, f_{vol}, f_{wear}, f_{alt}, f_{avail}, f_{skill}, f_E
11	Kühn (1984)	f_s, f_{fill}, f_{swing}, f_{depth}, f_{dump}, f_{vol}, f_{skill}, f_E
12	Liebherr (2003)	f_s, f_{fill}, f_{skill}, f_E
13	Nunnally (2007)	f_s, f_{fill}, $f_{swing\text{-}depth}$, f_E
14	Peurifoy and Schexnayder (2002)	f_s, f_{fill}, $f_{swing\text{-}depth}$, f_{skill}, f_E

Source: Own study.

2.3 Critical evaluation published of literature

From a qualitative point of view, the literature review has demonstrated two basic trends in estimating equipment-intensive construction productivity on the basis of a process-oriented technique. The first is characterised by the so-called 'German-oriented methodologies' (Group A), which are essentially based on Garbotz (1966) and BML (1983). The latter was developed in Germany by a common committee of the Central Association of the German Construction Companies (Zentralverband des Deutschen Baugewerbes) and the Federation of the German Construction Industry (Hauptverband der Deutschen Bauindustrie). These methodologies are not only used in German-speaking countries, but rather have established a computational framework that is still in use as well as directly transferrable and applicable in a cross-country and cross-industry fashion (Naskoudakis and Petroutsatou 2016; Ng et al. 2016). Their assumptions stem from statistical analysis of on-site measurements and historical data of real construction operations. The second trend is based on the so-called 'Anglosaxonic-oriented methodologies' (Group B) that are represented by both the equipment manufacturers' methodologies (Caterpillar, Komatsu, Liebherr, Volvo) and the textbook editions (e.g. Peurifoy and Schexnayder 2002; Nunnally 2007). These methodologies are very commonly used, due to their accessibility as well as versatility, partly explained by the use of the English language, which eliminates any comprehensive barriers amongst construction operatives. Both sets of methodologies were chosen for this research as they essentially represent two 'estimation philosophies', thus resulting in an objective testbed for their comparative evaluation. All selected methodologies share the same basic concepts in estimating excavation productivity, namely the inclusion of (a) bucket rated capacity, (b) cycle time and (c) productivity factors in the analysis. For clarity reasons, it should be noted that, in the context of this research, the 'productivity factors' are defined as correction coefficients in numerical form, which adjust the theoretical productivity (Q_{th}) to the actual or effective productivity (Q_{eff}), as presented in Eq. (1). Despite their similarities, the two main methodological groups present also significant differences, as shown in the previous paragraphs and as further scrutinised in the following paragraph.

This section aims at providing a more detailed, comparative analysis of the physical parameters presented in Eq. (1), along with their explanation in Section 2.2. First, each methodology's mathematical expression for productivity estimation is built by adjusting Eq. (1) according to the respective assumptions of Table 1. For example, for Komatsu (2013), the estimation formula is shaped as $Q_{eff} = V_{SAE}/t_c * f_s * f_{fill} * f_{depth}\ f_E$. The main similarities and differences in their computational approach are presented below:

- **Rated bucket capacity:** As explained in Section 2.2, there is a 15%–20% difference in estimating bucket heaped nominal capacity, between Group A (V_{CECE} with angle of repose 1:1) and Group B (V_{SAE} with angle of repose 1:2) methodologies. This practically means that a direct comparison of the yielded productivity estimates between the two groups is statistically valid only under the prerequisite of a proper adjustment in the estimation of rated bucket capacity.
- **Cycle time:** Group A methodologies, in principle, specify theoretical cycle time according to the bucket's nominal capacity, soil type and soil excavability category, which is based on the DIN 18300 standard. For example, the theoretical cycle time for soil types of high excavability (e.g. gravel, sand) in Group A methodologies can be rendered in terms of the expression, $t_c = -0.50\ V_{CECE}^2 + 4.19 * V_{CECE} + 13.13$ (sec). On the other hand, Group B methodologies follow merely the manufacturers' approach, where cycle time is associated with the equipment's engine power (see Figure 1 below). In general, the bucket size is indirectly related to the engine power, in the sense that the larger the bucket, the more powerful the equipment. However, the difference in the cycle time estimation approach between Group A and Group B methodologies yields differing productivity estimates, respectively.

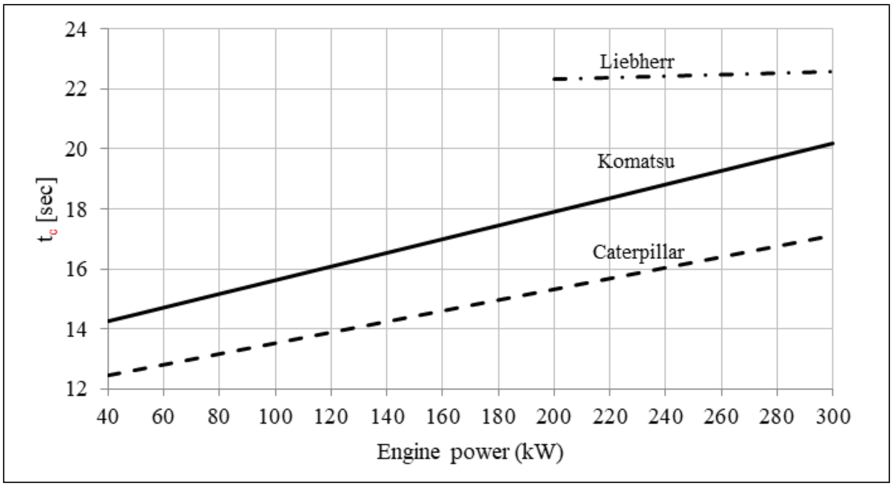

Fig. 1: Comparative estimation of cycle time according to equipment's engine power for equipment manufacturers' manuals. (*Source*: Own study).

- **Swell factor (f_s):** The most scientifically acceptable way to define the swell factor would be the experimental specification of its value under real construction site conditions. For validity reasons, a common swell factor is defined for all estimation methodologies, since it relates to the soil conditions and does not depend on the estimation approach.
- **Productivity factors (f_i):** The effect of the productivity factors defined in the previous section is expressed through numerical coefficients stemming from the differing assumptions of Group A and Group B methodologies. The value of these coefficients is summarised in Table 2 and Figure 2 below. Group B methodologies are diversified in those stemming from the equipment manufacturers' handbooks (Caterpillar, Komatsu, Liebherr, Volvo) and the ones corresponding to textbook editions (Nunnally; Peurifoy and Schexnayder) for clarity reasons.

The comparative evaluation of the productivity factors presented in Table 2 stresses the differences in input data requirements for each method, in order to yield excavation productivity estimates. More specifically, for the bucket fill factor (f_{fill}), the job efficiency factor (f_E) and the bucket teeth wear factor (f_{wear}), the presented analysis is rather comprehensive. As we move on, it is rather interesting to note that the operator skill factor (f_{skill}) is defined in a rather fuzzy logic: poor, average, good and excellent operators for Group A methods, and poor, average and excellent for Group B methods. A significant differentiation is that Group A methods imply a possible positive influence ($f_{skill} > 1$), whereas Group B methods consider the operator to have a negative ($f_{skill} < 1$) or neutral influence ($f_{skill} = 1$). The availability coefficient is either calculated based on the equipment's operating hours (Group A) or by a specific percentage value (Group B). Group A methodologies define the swing angle (f_{swing}) and excavation depth (f_{depth}) factors according to the graphs presented in Figures 2a and 2b. On the other hand, Group B methodologies do not define a specific coefficient. Instead, they provide a range of values for the theoretical cycle time and subsequently define specific job conditions (e.g. excellent, above average, average, below average, severe) for which the cycle time should be adjusted. The rationale is to take an average cycle time estimation for 'above average' conditions (i.e. swing angle < 60° and depth to 50% of machine's maximum capability) and increase or decrease the cycle time values for worse and better job conditions, respectively. Only textbook methods of Group B define a combined swing angle and digging depth factor (see Figure 2d), by implying that for a specific increase rate in swing angle and respective decrease rate in excavation depth, productivity is held constant ($f_{swing\text{-}depth}$ = constant).

Tab. 2: Productivity factors' values specification and comparative analysis.

	Productivity estimation methodology		
Productivity factor	**Group A**	**Group B**	
		Equipment manufacturers	**Textbook methodologies**
Bucket fill factor (f_{fill})	Values based on the DIN 18300:2012 standard within the range 0.72–1.40	Indicative values within the range 0.60–1.20	
Job efficiency factor (f_E)	Same approach for all methodologies: $f_E = (60–Σ[\text{Delays in min}])/60$		
Operator skill factor (f_{skill})	Values according to operator's skill and experience	Implicit effect included in cycle time estimation	
Equipment availability factor (f_{avail})	Values according to equipment's working hours within the range 0.65–1.00 (i.e. <1,000 hr f_{avail} = 1; 3,500–5,000 hr f_{avail} = 0.65)	No specific values' range, but empirically defined as a percentage with probable value ~80%	-
Swing angle factor (f_{swing})	See Figure 2a	Implicit effect included in the cycle time estimation	
Excavation depth factor (f_{depth})	See Figure 2b	Same as f_{swing}	
Combined swing angle and digging depth factor ($f_{swing\text{-}depth}$)	-	-	See Figure 2d
Bucket dump factor (f_{dump})	f_{dump} < 1 for targeted dump	-	-
Excavator-truck volumes match factor (f_{vol})	See Figure 2c	-	-
Bucket teeth wear factor (f_{wear})	f_{wear} < 1 for worn teeth	-	-
Altitude factor (f_{alt})	f_{alt} < 1 for >300 m altitude	f_{alt} < 1 for >760 m altitude	-

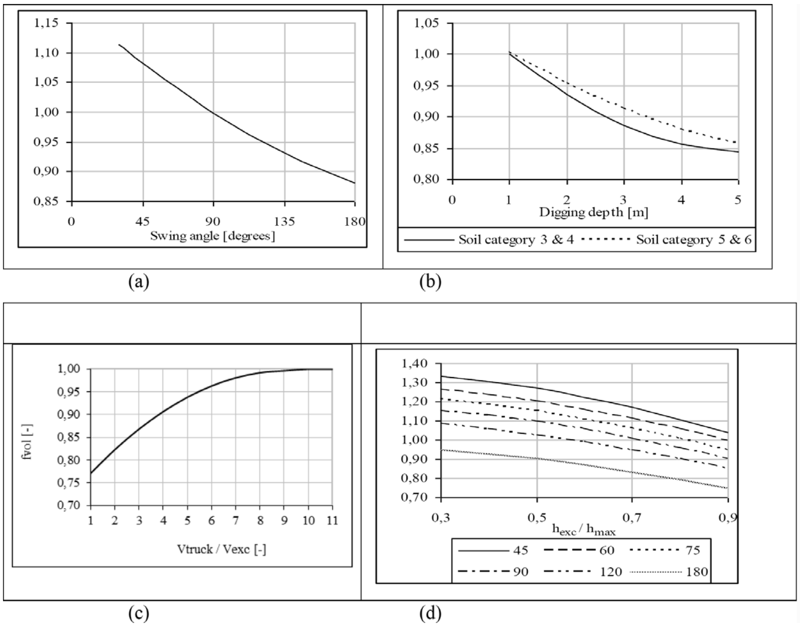

Fig. 2: Values specification for productivity factors' coefficients (V_{truck}, truck volume; V_{exc}, excavator bucket volume; h_{exc}, excavation depth; h_{max}, maximum excavation depth). (a) Swing angle coefficient. (b) Digging depth coefficient for different DIN 18300 categories (3&4: soft soil, 5&6: hard soil). (c) Excavator – truck volume match factor coefficient. (d) Swing – depth coefficient for different swing angles. (*Source*: Own study).

The bucket dump factor (f_{dump}) implies an increase in cycle time due to the need for manoeuvring and careful manipulation of the bucket; however, only Group A methods provide specific values. The same applies in the case of the excavator-truck volume match factor (f_{vol}) in the sense that Group A methods are based on the graph illustrated in Figure 2c. Group B methods (especially Caterpillar) associate the match factor with minimising idle times in excavation-truck systems; however, they do not provide a specific values' range for its determination. Lastly, the altitude factor (f_{alt}) is similarly defined by both groups, with their differentiation lying in the altitude threshold for decreasing f_{alt} values, i.e. >300 m altitude for Group A and >760 m altitude for Group B methods, as shown in Table 2.

3 Research methodology

The previously presented analysis has demonstrated practically that, irrespective of the selected productivity estimation methodology, the inclusion of the productivity factors' variability in the analysis is a complicated issue. As such, apart from the main research question formulated in Section 2.2 (How do different estimation methodologies incorporate the aforementioned productivity factors in their calculations and what is the extent of their variability?), two additional important questions have to be addressed by the analysis: (a) 'How do the differing assumptions of the estimation methodologies affect the outputs?' and (b) 'What is the most suitable computational approach for a particular construction case?'. The answer to the posed research questions is provided through the proposed research methodology, which is essentially a three-stage process, whose steps are explained in the next paragraphs.

3.1 Stage A: Analysis of excavation scenario

The first stage entails the definition of the scope. According to the project scenario, each one of the 14 estimation methodologies is adapted to the operational context, and the operational factors are given specific values to reflect the on-site conditions. A range of values is assigned for continuous coefficients (e.g. cycle time), whereas for discrete coefficients focus is given on their respective attributes in a fuzzy logic (e.g. soil type can be 'loose soil', 'clay' etc.). The estimator has to define the basic characteristics of the deployed equipment, as well as the excavator cycle time for each estimation methodology according to the project characteristics. The data collection rationale is based on the use of multiple sources of evidence, in order to achieve the required triangulation of project data that would enhance the research validity. More specifically, the created research database includes the following data taxonomy:

- **Documentation:** It includes contract documents (e.g. technical description, project budget, bill of quantity for earthmoving works, project drawings), daily project diaries-logs containing an analytical description of the executed works, the deployed personnel/equipment and consumed materials, as well as any ancillary project document that aids in the comprehensive representation of the project operational conditions.
- **Archival records:** It entails field notes (e.g. hand written, electronic files) produced by construction personnel and maps and charts containing the project's geographical characteristics, as well as survey data that benchmarked the project progress.
- **Direct observation:** It was enabled by the physical presence in the construction site during the project execution phase, which enhanced the establishment of a data collection protocol and collection of observational evidence. The field measurements included a study of the project daily report, which depicts all project resources (e.g. equipment, personnel, materials). In addition, all earthmoving activities are recorded according to the project's work breakdown structure (WBS), and all items of equipment are associated with their operators. Moreover, executed quantities are attributed to every construction activity on a daily basis, so as to have a holistic overview of the project's progress and performance metrics. The observational evidence is enhanced with photographic and video material (e.g. time-lapse videos), in order to create a historical digital database.
- **Data collection format and period:** An electronic database in spreadsheet format was created for the whole earthmoving activities execution phase, namely January to August 2019. In total, 157 daily datasets were collected, which represented the actual dataset from which research inferences emerged.

3.2 Stage B: Productivity estimation and comparative evaluation

Once all productivity factors and other variables have been set, the analysis for the selected construction scenario is conducted. The actual collected project data aid in shaping the project parameters (e.g. soil, swing angle, excavation depth etc.), and subsequently the main productivity variables (i.e. cycle time, productivity factor coefficients) are derived from each one of the 14 selected estimation methodologies. If the underlying assumptions and respective productivity factors are common to more than one estimation methodology, then different values are given to reflect each methodology's unique approach. A comparative evaluation of the yielded results is performed, in order to specify the variability in the produced metrics. Normally, the results are presented in a tabular and graphical format, so as to enable the direct comparison amongst the different estimation methodologies.

3.3 Stage C: Sensitivity analysis and conclusion of decision making process

Lastly, the estimator selects one or more operational factors against which the estimation methodologies' variation will be examined. In our case, the sensitivity analysis will be performed for varying values of the swing angle and excavation depth, since they are considered fundamental productivity variables in excavation works. Finally, a decision making process has to be specified, in order to select the preferred estimate.

4 Results

4.1 Stage A: Analysis of excavation scenario

The selected project is a highway construction project in Crete, Greece. It entails the construction of a 3 km roadway which, inter alia, includes the excavation of loose soil (267.000 m^3). It is a €12.5 million project with a contractual deadline of 18 months, whereas the excavation works have a duration of 8 months. The excavator-truck system includes three excavators (Caterpillar 345B, Caterpillar 330 and O&K RH16), one loader (CAT 966H) and four trucks of the same type (Caterpillar 725C). The material is transferred in a dumping site 3 km away from the excavation front. The average excavation depth is 3 m and the average required swing angle for the excavators is 120°. The equipment operators are relatively experienced and the working conditions are considered to be average.

4.2 Stage B: Productivity estimation and comparative evaluation

- **Excavator – truck scenario**

After the description of the scope of operations, the 14 estimation methodologies presented in the previous section are selected for a deterministic analysis. Their yielded results are presented in Table 3 and refer indicatively to the excavator's CAT 345B productivity. Subsequently, a more summarising view of the estimation methodologies' results for all three excavators in loose soils is presented in Figure 3.

It is logical to obtain an increased productivity rate for CAT 345B, since it is equipped with a larger bucket (4 m^3) in relation to the CAT 330 and O&K RH16 excavators, which are equipped with a 1.76 m^3 and 2.08 m^3 bucket, respectively. It is also evident, though, that the equipment manufacturers' manuals (Caterpillar, Komatsu, Liebherr and Volvo) provide higher productivity values in comparison to the respective estimation methodologies from Germany or the textbook editions. This is attributed, from a glance at the respective table, to the smaller amount of productivity factors taken into account by the equipment manufacturers' methods, thus leading to more optimistic productivity values.

- **Excavator and Loader – truck scenario**

This scenario examines the combinatory loading of loose material with the use of both excavators and loaders onto trucks. Figure 4 depicts the results for the productivity estimations for the aforementioned working paradigm.

All productivity estimates lie within a narrow range for all examined methodologies. It is, interestingly, observed that the there is an increased performance of the CAT 330–CAT 725C system rather than the CAT 345B–CAT 725C system, although CAT 330 has a smaller nominal bucket capacity than CAT 345B. At the same time, it is also observed that O&K RH16 yields similar productivity values with CAT 345B. Productivity is directly affected by the number of loading cycles and the truck fill factor, which are derived based on the nominal equipment capacity and the fill factors taken into account by each estimation methodology. Respectively, in the loader deployment scenario, the German-oriented methodologies (BML, Bauer, Garbotz, Hoffmann, Kühn, Hüster and Girmscheidt) present higher productivity values than the rest of the set. Once again, productivity is substantially affected by the number of loading cycles, which depends on the truck fill factor, as well as the loader's bucket fill factor.

Tab. 3: Comparative evaluation of CAT 345B excavation productivity.

Equipment – model:	**Excavator – Caterpillar 345B**											
Soil type	**Loose soil**											
Work method	**Excavation and soil disposal on truck**											
	Komatsu (2013)	**Caterpillar (2016)**	**Liebherr (2003)**	**Volvo (2015)**	**Nunnally (2007)**	**Peurifoy and Schexnayder (2002)**	**BML (1983) and Hoffmann (2006)**	**Kühn (1984)**	**Hüster (2005)**	**Bauer (2007)**	**Girmscheidt (2010)**	**Garbotz (1966) and Kotte (1997)**
$V_{(SAE/CECE)}$ (m^3)	4	4	4	4	4	4	3.48	3.48	3.48	4	4	3.48
t_{exc} (sec)	20.50	20.00	23.00	19.50	24.00	24.00	22.00	22.00	22.00	22.00	22.00	22.00
f_s	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23
f_{fill}	1.15	1.05	1.10	1.05	1.00	1.05	1.20	1.20	1.20	1.20	1.20	1.20
f_{depth}	1.30	×	×	×	×	×	1.13	1.13	1.13	1.13	1.13	1.13
f_{swing}	×	×	×	×	×	×	0.95	0.95	0.95	0.95	0.95	0.95
$f_{swing\text{-}depth}$	×	×	×	×	1.05	0.88	×	×	×	×	×	×
f_{dump}	×	×	×	×	×	×	0.90	0.90	0.90	0.90	×	0.90
f_{skill}	×	0.75	0.85	×	×	0.75	×	0.71	0.80	×	0.80	0.80
f_{avail}	×	×	×	0.85	×	×	×	×	0.80	×	0.85	0.85
f_{vol}	×	×	×	×	×	×	0.92	0.92	0.92	0.90	0.90	0.92
f_{wear}	×	×	×	×	×	×	×	×	×	0.90	0.90	0.90
f_{alt}	×	×	×	×	×	×	×	×	×	×	×	0.99
f_E	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Q (m^3/h)	573.23	523.06	540.02	608.00	498.15	383.58	438.60	311.40	280.70	444.08	335.53	265.74

Source: Own study.

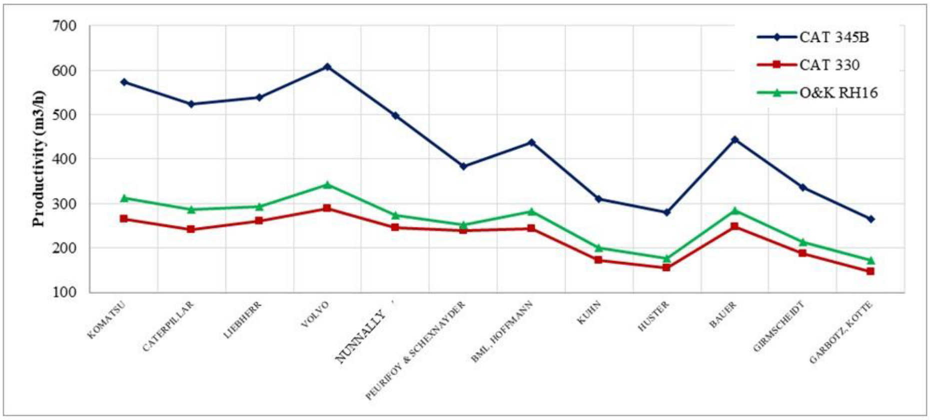

Fig. 3: Variation of excavator productivity in relation to equipment type.
(*Source*: Own study).

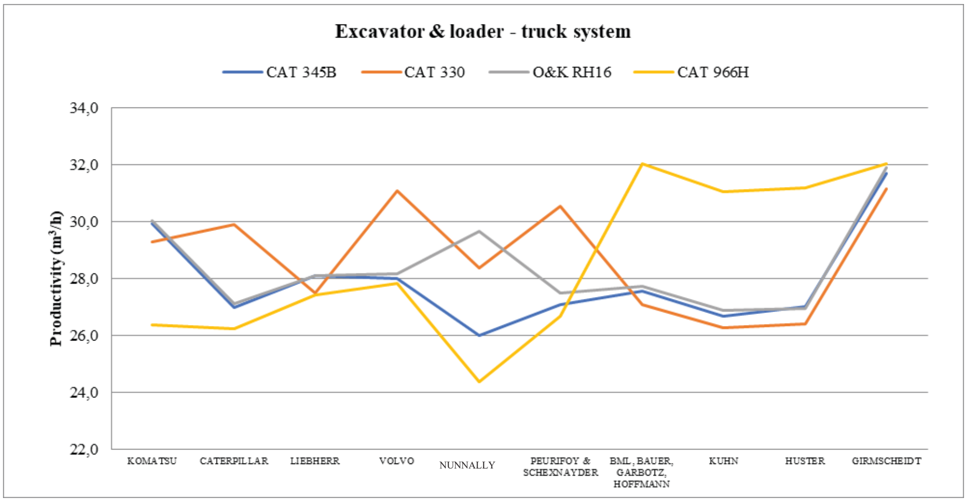

Fig. 4: Productivity estimation results for combinatory operation of excavator and loader – truck system.
(*Source*: Own study).

Consequently, alternative working patterns for all deployed equipment were examined, as presented in Table 4 and Figure 5. The examined combinations included at least the excavator CAT 345B and the loader CAT 966H with addition of other equipment per case (e.g. excavators CAT 330/O&K RH16), since they represent the base working approach for the actual project that served as the case study.

For the Komatsu and Liebherr methodologies, the prevailing scenarios are 1 and 6, which present a very small difference in the productivity estimates. Scenario 1 pertains to the combination of the operation of the excavator CAT 345B with one truck and the loader CAT 966H with the rest of the trucks, without deploying the other two excavator models. Scenario 6, which yields the maximum productivity according to the Nunnally methodology, includes the combination of the excavator CAT 345B and the loader CAT 966H, where each of the aforementioned equipment is assigned with one truck. The other two trucks of the fleet work with the excavator O&K RH16.

For the Caterpillar, Volvo and Peurifoy & Schexnayder methodologies, Scenario 4 is the combination with the optimum productivity estimates. In that scenario, excavator CAT 345B works with one truck and the excavator CAT 330 cooperates with two trucks, while the remaining truck is assigned to the loader CAT 966H.

Tab. 4: Equipment deployment combinations and productivity results.

Available equipment	Working scenarios – operational combinations								
	1	2	3	4	5	6	7	8	9
	Four trucks – CAT 725C								
One excavator – CAT 345B	3	2	2	1	1	1	1	1	1
One excavator – CAT 330	-	-	1	2	1	-	1	-	-
One excavator – O&K RH16	-	-	-	-	1	2	-	1	-
One loader – CAT 966H	1	2	1	1	1	1	2	2	3
Work type	**Transportation of loose soil**								

Working scenarios	**Komatsu (2013)**	**Caterpillar (2016)**	**Liebherr (2003)**	**Volvo (2015)**	**Nunnally (2007)**	**Peurifoy and Schexnayder (2002)**	**BML (1983), Bauer (2007), Garbotz (1966) and Hoffmann (2006)**	**Kühn (1984)**	**Hüster (2005)**	**Girmscheidt (2010)**
1	116.21	107.22	111.78	111.82	102.42	107.98	114.76	111.12	112.30	127.17
2	112.65	106.47	111.09	111.66	100.79	107.57	119.23	115.47	116.46	127.51
3	115.57	110.13	111.15	114.90	104.78	111.41	114.30	110.70	111.67	126.63
4	114.93	113.03	110.53	117.97	107.14	114.84	113.83	110.28	111.03	126.09
5	115.68	110.26	111.14	115.08	108.43	111.80	114.46	110.89	111.59	126.82
6	116.42	107.49	111.76	112.19	109.72	108.76	115.09	111.49	112.15	127.55
7	112.01	109.38	110.47	114.73	103.15	111.00	118.77	115.05	115.83	126.97
8	112.75	106.61	111.08	111.84	104.44	107.96	119.40	115.66	116.38	127.70
9	109.09	105.72	110.41	111.49	99.17	107.15	123.71	119.82	120.62	127.84

Source: Own study.

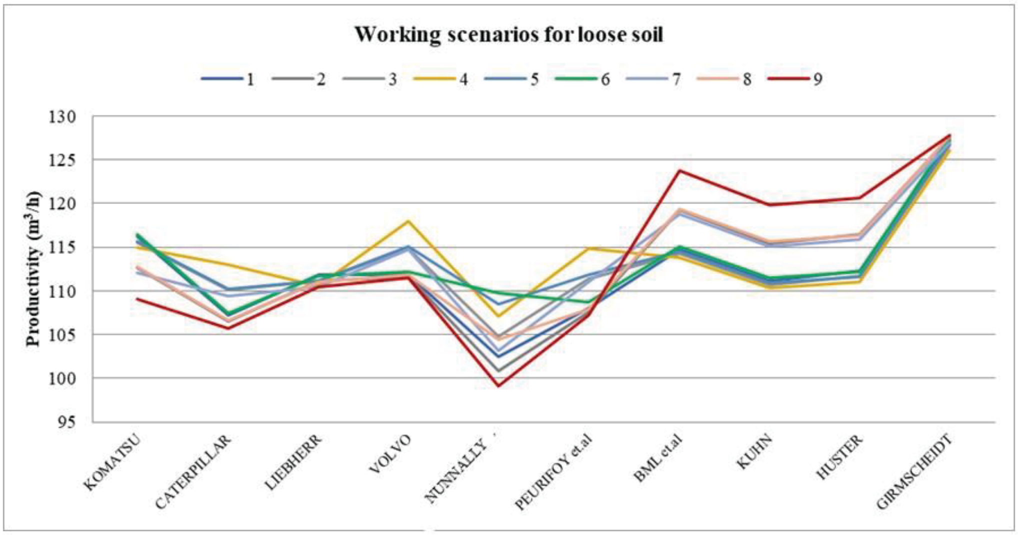

Fig. 5: Productivity estimation results for combinatory operation of excavator and loader – truck system. (*Source*: Own study).

For the German-oriented methodologies (BML, Bauer, Garbotz, Hoffmann, Kühn, Hüster and Girmscheidt), Scenario 9 is the most prevailing solution. In this working pattern, the excavator CAT 345B works with one truck, while the rest of the three trucks are assigned to the loader CAT 966H. This result is easily explained by looking at Figure 5, where there is a significant difference in productivity estimations for the loader deployment scenario in relation to the other alternatives that include the excavators. Interestingly enough, Scenario 9 is the combination with the minimum productivity estimates, according to the methodologies of Komatsu, Caterpillar, Liebherr, Volvo, Nunnally and Peurifoy & Schexnayder. On the other hand, Scenarios 1, 4 and 6, while being the prevailing alternatives for the aforementioned methodologies, present relatively low productivity estimates for the German-oriented methodologies (BML, Bauer, Garbotz, Hoffmann, Kühn and Hüster).

4.3 Stage C: Sensitivity analysis and conclusion of decision making process

The sensitivity analysis for every estimation methodology is conducted for the assessment of the CAT 345B excavator's productivity, by varying the swing angle and the excavation depth. The initial estimations were performed for a swing angle 120° and excavation depth 3 m, which are considered as the baseline reference conditions of the specific construction scenario.

The percentage for the increase and decrease of the excavators' productivity is examined for discrete swing angle values at 60°, 90° and 180°. Table 5 and Figure 6 below present the respective results and provide the magnitude of the variation in percentage format (%). According to the equipment manufacturers' approach (i.e. Caterpillar, Komatsu, Liebherr, Volvo), the variation of the swing angle affects the excavator cycle time. For the textbook editions (i.e. Nunnally, Peurifoy & Schexnayder), the variation of the swing angle is expressed through the combined swing angle and digging depth factor ($f_{swing\text{-}depth}$), where these methods present larger variability percentages. The German-oriented methodologies adopt the assumptions of BML (1983), thus explaining the same variation percentage for all of them. Their sensitivity is marginally smaller in relation to the other estimation methodologies. It is easily observed, though, that irrespective of each methodology's results, the trend remains similar, meaning that excavation productivity is decreased as the swing angle increases.

In the same fashion, Table 6 and Figure 7 present the sensitivity analysis for every estimation methodology by varying the excavation depth at 2 m, 4 m and 5 m. For Caterpillar (2016), the variation of the excavation depth results in modifications in the excavator cycle time. In Komatsu (2013) and BML (1983), the effect of excavation depth is expressed through the productivity factor f_{depth}, and it is observed that Komatsu (2013) is not affected in its productivity results by the variation of the excavation depth. Lastly, the German-oriented methodologies

Tab. 5: Productivity variation for CAT 345B excavator based on swing angle.

	Productivity results (m³/h) and variations depending on the swing angle						
	120°	60°	Percentage of variation	90°	Percentage of variation	180°	Percentage of variation
Komatsu (2013)	573.23	671.50	17.14%	618.49	7.89%	534.15	−6.82%
Caterpillar (2016)	523.06	581.18	11.11%	550.59	5.26%	475.51	−9.09%
Liebherr (2003)	540.02	621.03	15.00%	591.45	9.52%	496.82	−8.00%
Volvo (2015)	608.00	658.67	8.33%	634.01	4.28%	564.57	−7.14%
Nunnally (2007)	498.15	583.55	17.14%	536.10	7.62%	441.22	−11.43%
Peurifoy and Schexnayder (2002)	383.58	505.62	31.82%	435.88	13.64%	309.48	−19.32%
BML (1983) and Hoffmann (2006)	438.60	484.76	10.53%	461.68	5.26%	406.28	−7.37%
Kühn (1984)	311.40	344.18	10.53%	327.79	5.26%	288.46	−7.37%
Hüster (2005)	280.70	310.25	10.53%	295.48	5.26%	260.02	−7.37%
Bauer (2007)	444.08	490.82	10.53%	467.45	5.26%	411.36	−7.37%
Girmscheidt (2010)	335.53	370.84	10.53%	353.19	5.26%	310.80	−7.37%
Garbotz (1966) and Kotte (1997)	265.74	293.71	10.53%	279.72	5.26%	246.16	−7.37%

Source: Own study.

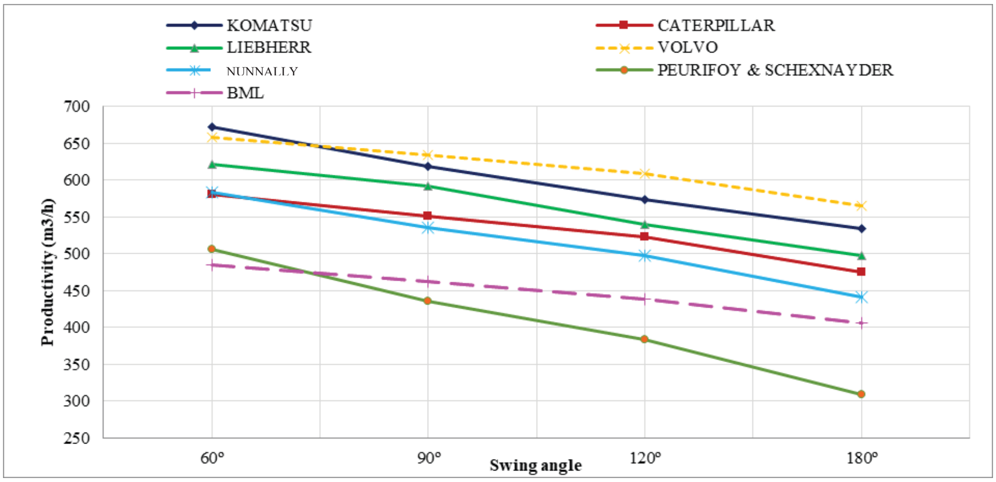

Fig. 6: Graphical illustration of productivity variation for CAT 345B excavator based on swing angle. (*Source*: Own study).

Tab. 6: Productivity variation for CAT 345B excavator based on excavation depth.

	Productivity results (m³/h) and variations depending on the excavation depth						
	3 m	**2 m**	**Percentage of variation**	**4 m**	**Percentage of variation**	**5 m**	**Percentage of variation**
Komatsu (2013)	573.23	677.45	18.18%	573.23	0.00%	573.23	0.00%
Caterpillar (2016)	523.06	550.59	5.26%	498.15	−4.76%	475.51	−9.09%
Liebherr (2003)	540.02	540.02	0.00%	540.02	0.00%	540.02	0.00%
Volvo (2015)	608.00	608.00	0.00%	608.00	0.00%	608.00	0.00%
Nunnally (2007)	498.15	512.38	2.86%	464.94	−6.67%	445.96	−10.48%
Peurifoy and Schexnayder (2002)	383.58	361.78	−5.68%	353.06	−7.95%	326.91	−14.77%
BML (1983) and Hoffmann (2006)	438.60	458.90	4.63%	423.60	−3.42%	409.60	−6.61%
Kühn (1984)	311.40	325.82	4.63%	300.76	−3.42%	290.81	−6.61%
Hüster (2005)	280.70	293.70	4.63%	271.11	−3.42%	262.14	−6.61%
Bauer (2007)	444.08	464.64	4.63%	428.90	−3.42%	414.72	−6.61%
Girmscheidt (2010)	335.53	351.06	4.63%	324.06	−3.42%	313.34	−6.61%
Garbotz (1966) and Kotte (1997)	265.74	278.04	4.63%	256.65	−3.42%	248.17	−6.61%

Source: Own study.

adopt again the assumptions of BML (1983) and present a variability of less than 7% in their estimates.

5 Discussion

The research has presented a multifaceted view of excavation, loading and transportation productivity for a typical earthworks project. All presented results, if interpreted under the prism of the underlying theoretical assumptions presented in Table 1, yield interesting inferences that emerge from the study. First, the standalone estimation of excavation productivity for each one of the three excavators (CAT 345B, CAT 330 and O&K RH16) corroborates other research outcomes, namely that the equipment manufacturers' estimation methodologies are more optimistic than the more analytic approaches in published literature (i.e. textbook, German-oriented). The variability of

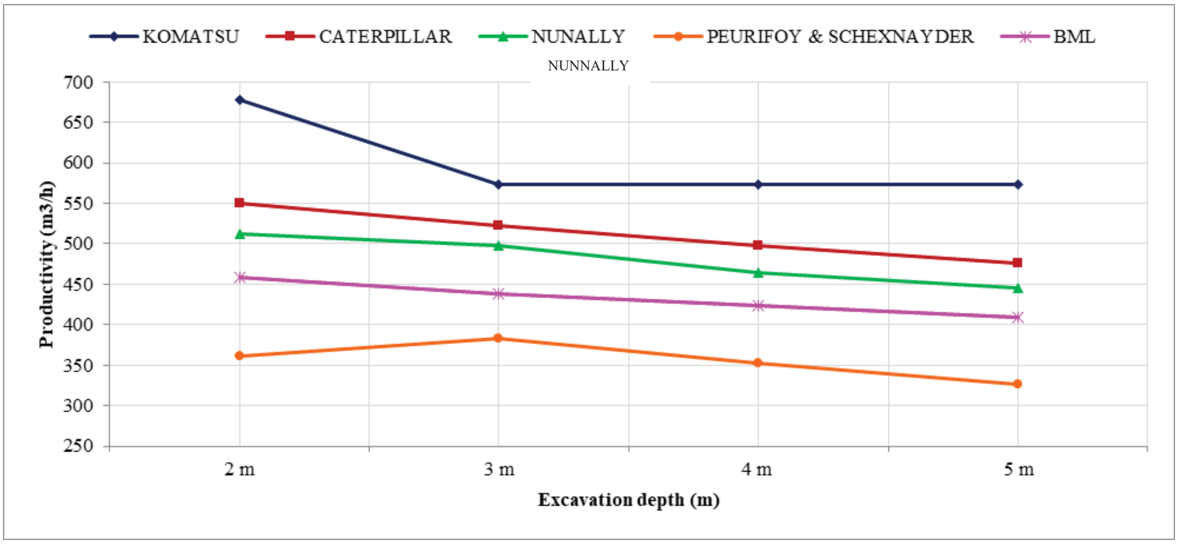

Fig. 7: Graphical illustration of productivity variation for CAT 345B excavator based on excavation depth. (*Source*: Own study).

the produced estimates is attributed to the different set of productivity factors taken into account and the differing values' range for common factors per estimation methodology. It is characteristic that the productivity estimates for CAT 345B in Table 3 present more than 110% variability, hence denoting the intense differences in the methodologies' theoretical assumptions.

The combinatory analysis per equipment type resulted in significant differences between different types of equipment (e.g. excavator vs loader). There is a systematic pattern where the loader is found more productive than the excavator by the German-oriented methodologies, while the exact opposite trend is observed for the rest of the examined estimation methodologies. Thus, another important inference is that the theoretical assumptions should be also critically reviewed for every equipment type before reaching managerial decisions that could affect the project progress. The latter is even more enhanced, in the case of the combinatory deployment of all involved equipment as presented in Table 4 and Figure 5. In the most characteristic scenario, where the excavator CAT 345B works with one truck and the loader CAT 966H works with three trucks (CAT 725C), the two groups of methodologies (i.e. German-oriented vs textbook/equipment manufacturers) yield almost opposite estimates. Therefore, a practical guideline could be that the two groups of estimation methodologies could serve as the 'best-case' and 'worst-case' benchmark, thus denoting the limits of the possible productivity estimates. In practice, the actual or effective on-site productivity usually lies within that range. In fact, the latter was corroborated by the comparison of the actual set to the investigated estimation methodologies. More specifically, the actual data set presented a large variability in daily measurements that had to be attributed to both operational (e.g. working method, project location etc.) and non-technical parameters (e.g. equipment downtime, adverse weather conditions etc.). As such, the actual dataset lay within the designated range yielded by the estimation methodologies. Due to the increased variability, it was difficult to determine which methodology better reflected the actual on-site measurements. A possible mitigation measure towards resolving this issue could be the extension of the observational period, in order to include more actual daily measurements and conduct long-lasting statistical analyses. It is still valid to state, though, that the observed variability in the daily measurements may explain why the investigated estimation methodologies still remain acceptable within the construction estimation paradigm.

Lastly, the sensitivity analysis that was conducted on the two main productivity factors affecting excavation productivity (i.e. swing angle and excavation depth) illustrated the significance of the working conditions' effect on productivity. The main inference is that all estimation methodologies present a similar, gradual decreasing trend on productivity, as the swing angle increases. In a similar fashion, the same trend is observed for the excavation depth as well. Hence, it could be stated that, as long as the estimator has chosen which estimation methodology to adopt, the alternative working conditions' scenarios bear a specific degree of predictability, at least in their expected trends. As a general remark, it should be stated that all the aforementioned inferences were easily derived due to the deterministic research approach that actually provides a straightforward notion for the estimates' variability. Thus, it should be regarded as a research enabler rather than limitation, although the deterministic analysis cannot present complex analytical results. Besides, the main research contribution to the existing body of knowledge is the presentation of a methodological framework that may be adapted to different construction scenarios in an easy and practical manner, rather than establishing a computationally complex algorithmic approach for estimating purposes. However, the examination of the presented methodologies under different analytical tools might constitute a useful research expansion step. For example, the application of queueing theory concepts that have been extensively used in mining operations or even discrete-event simulation that allows the incorporation of complex project variables in the analysis, could shed light on the applicability boundaries for the investigated productivity models. Of course, in such a case the input data must be enhanced in order to include probabilistic assumptions such as trucks arrival rates, processing rates, truck-loader service times etc. Such parameters are often developed from field observations. In any case, when applying probabilistic models (e.g. queueing, simulation) it is fundamental for the modeller to ensure that the investigated system reflects a 'steady-state' operation, namely that a sufficient period of time has passed that allows the system to 'settle down' and reach a steady-state level of operation. Lastly, as a further evolutionary research step, the presented methodology can be incorporated in an information system, so as to automate the production of estimates that could facilitate construction operatives in different project stages (e.g. tender, construction, operation etc.).

6 Conclusions

The presented research has proven that the assessment of construction productivity is a rather multifaceted issue, which is heavily affected by the estimation methodologies and their respective productivity factors. The 14 estimation methodologies were analysed as per their constituent productivity factors, and they were adapted to the real construction activities of a specific project in hand.

The comparative evaluation of the results corroborated the empirical notion that the equipment manufacturers' estimation methodologies tend to be more optimistic in their assessments. Moreover, the German-oriented methodologies yield lower productivity results than the rest of the scrutinised methodologies. The subsequent sensitivity analysis also verified that swing angle and excavation depth are key productivity drivers in excavation operations. Once again, the equipment manufacturers' approaches presented a larger variability in relation to the German-oriented methodologies.

The main research contribution to the body of knowledge associated with construction and labour productivity is twofold: to start with, it is the first concurrent comparative evaluation of process- and equipment-oriented construction productivity estimation methodologies that represent two major philosophies: the German-based methods, which largely rely on statistical elaboration of project data presented in a graphical format, and the Anlgosaxonic-based methods, which stem from manufacturers' manuals and textbook editions and represent the inclusion of empirical knowledge expressed in both heuristic rules and performance diagrams. Secondly, it adopted an innovative research approach by analysing commonly used productivity factors (e.g. swing angle factor) not only on the basis of their values' range, but also against their underlying theoretical assumptions, thus illuminating the root causes of their variability. In addition, this research should be regarded as a practical tool that is directly applicable to other projects, countries or industries for the following reasons: (a) it contains estimation methodologies that refer to versatile equipment (e.g. excavators), deployed in common construction activities that are executed in a similar fashion independent of country or project characteristics; (b) all reviewed estimation methodologies are largely acknowledged and utilised amongst construction operatives, as mentioned in the literature review section. It is characteristic that the manufacturers' manuals are issued by organisations that have a global presence in all continents and hence their productivity assumptions are readily applied in projects around the world.

Irrespective of the applied approach, the selection of the most appropriate estimate from the yielded results remains the main issue, since each methodology is based on its own theoretical assumptions that are reflected on the defined productivity factors and their respective values. As such, the selection must be based on subjective inputs from the analyst, who may also introduce some sort of weighting or ranking amongst the different methodologies. Therefore, the possibility of applying different modelling techniques, such as stochastic simulation or statistical regression, can possibly be considered as a way of decreasing variance in single-point estimates of construction productivity.

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