



# An eco-approach to optimise efficiency and productivity of a hydraulic excavator



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## ABSTRACT

The depletion of fossil fuel and the ozone layer has been a global concern for decades. The International Organization for Standardization has published earth-moving machine sustainability standards for the industry to provide information to satisfy their customers' interests in their construction projects. Furthermore, steeply rising energy prices and the collapse of financial institutions in recent years have sparked demand for ways to improve individual energy efficiency. Original equipment manufacturers of earth-moving machines must address sustainability requirements, as well as remaining competitive and they aim to do this by improving machine efficiency, adopting advanced fleet management systems, providing operator training courses etc. Clearly high fuel efficiency is important to reduce depletion of fossil fuels and damage to the environment. However, the objectives of achieving the highest possible productivity ( $\text{m}^3/\text{h}$ ) and improving fuel efficiency ( $\text{kg}/\text{l}$ ) are often considered separately. Many equations have been formulated to measure a machine's highest possible productivity level, yet there is a lack of consensus between academia and industry sources on the terms which should be considered within such equations. Perhaps more importantly, none have explicitly considered the relationship between fuel efficiency and productivity, and only scant consideration is given to the role of operators in achieving optimum productivity for fuel efficiency. Therefore, this paper presents an eco-approach to enable operators to achieve optimal productivity for fuel efficiency of a hydraulic excavator. Hydraulic excavators are primarily designed for excavating with a bucket. Their ease of use, versatility and high productivity have won them major segments of the construction equipment market, therefore the focus on hydraulic excavators in this paper is justifiable. The research presented in this paper has adopted an applied research methodology to collect measurable, empirical evidence through scientific experiments in order to test several hypotheses that focus on the reduction of GHG produced by construction machines. The research has examined two variables, engine speed and bucket cut depth, to determine their effects on productivity and fuel efficiency of a hydraulic excavator. The experimental results show that the combinations of various engine speed settings and bucket cut depths can increase productivity by 30% and cut greenhouse gas emissions by 24%, consequentially moving 62% more spoil every hour for every litre of fuel consumed. The results also suggest that identifying the correct bucket cut depth is the key to significant improvements in productivity and reduction in greenhouse gas emissions. The paper therefore concludes that adoption of an appropriate construction machine operation style can help reduce the greenhouse gas emissions associated with hydraulic excavators. Hence, educating operators to select the right engine speed and bucket cut depth is a cost effective approach to lowering the operational costs and carbon emissions through lower fuel consumption and greater machine longevity.

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**Abbreviation:** BCD, Bucket Cut Depth; BS, British Standards; CAT, Caterpillar Incorporated; CECE, Committee for European Construction Equipment;  $\text{CH}_4$ , Methane; DECC, Department of Energy and Climate Change; DEF, Diesel Exhaust Fluid; DEFRA, The Department for Environment Food & Rural Affairs; DPF, Diesel Particulate Filter; EngD, Engineering Doctorate; GHG, Green House Gas; ISO, International Standard Organisation; JCB, J. C. Bamford Excavators Limited; KOM, Komatsu Limited;  $\text{N}_2\text{O}$ , Nitrous Oxide; NRMM, Non-Road Mobile Machinery; ODP, Ozone Layer Depletion; OEM, Original Equipment Manufacturer; PAR, Performance Ability Ratio; RPM, Revolutions Per Minute; SAE, Society of Automotive Engineers.

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## Nomenclature

### Descriptions/symbols & SI unit

Energy Consumption ( $E_{\text{con}}$ )	kWh
Fuel Efficiency	kg/l
Productivity	m <sup>3</sup> /h
Task Efficiency	kg/l
Density ( $P$ )	kg/m <sup>3</sup>
Lower Heating Value	kJ/kg
Energy Consumption	kWh
Productivity	m <sup>3</sup> /h
$V_{\text{cece}}$	m <sup>3</sup>
$t_{\text{th, x}}^{\text{exc}}$	min
Fuel Consumption Rate	l/h

## 1. Introduction

Under the climate change Act (2008), a target has been set for the UK to reduce at least 80% of its Green House Gas (GHG) emission level in 1990 by 2050. 7% and 8% of the total GHG emissions come from non-road mobile machinery (NRMM) within the business and agriculture sectors respectively (Grummer et al., 2013). The Department of Energy and Climate Change (DECC) claims about 33% of total CO<sub>2</sub> emissions in England are from on-site construction activities (Green Construction Board, 2010), of which 26% of total carbon emissions are due to plant and equipment use such as excavators or backhoe loaders (Chiang et al., 2014). These emissions pollute the environment and have impact on acidification and ozone layer depletion (ODP) (Elduque et al., 2014), and correspondingly are harmful to people (Zhang et al., 2014). Among construction machines, excavators are used extensively within the UK construction industry, due to their ease of use, versatility and high productivity, compared to other construction machines (Edwards et al., 2001). Under the European Commission directive 2012/46/EU, NRMM OEMs are under constant pressure to reduce GHG emissions, yet the pressure to maximise excavator productivity has also increased (Patel et al., 2001). This is due, at least in part, to fuel duty increases: the price of red diesel (a low tax fuel for registered agricultural and construction vehicles) rose from £0.55 per litre (in 2010) to £0.70 per litre (in 2013) (Agriculture and Horticulture Development Board, 2013). Excavator operators therefore have a dual challenge, firstly to lower fuel consumption in order to reduce cost, but without compromising machine productivity (m<sup>3</sup>/h), and secondly, to reduce fuel consumption such that GHG emissions will be reduced.

Most OEMs offer a range of machine modes on their machines to suit various task specifications (referred to hereafter as duties). A duty is a task which operators have to perform, such as tracking, trenching and loading (for example, an excavator can undertake over 15 different duties). A machine mode is designed to give customers and machines greater flexibility to deal with the challenges which commonly occur when performing various duties such as saving time, reducing fuel consumption or breaking through hard materials. However, such modes could be seen as restrictive to operators who have sufficient experience and expertise to manually adjust machine settings to optimise productivity and fuel efficiency.

The challenge of increasing excavator productivity while minimising fuel use is of growing importance for both industry and academic research. Tam attempted to use artificial neural networks

to develop a quantitative model for predicting productivity (Tam et al., 2002). It is also important to the UK to reduce GHG emissions (Mao et al. 2014). The need to better understand the nature of productivity related to fuel consumption in this specific context is critically important. Therefore, this paper investigates a novel, eco-approach specifically for operators to optimise productivity and fuel efficiency whilst operating a hydraulic excavator. A new, and important, variable, bucket cut depth (BCD), has been used in this research as a result of the recommendations from industries and academics mentioned in Sections 2,3 and 4. In previous studies BCD has been treated as a constant (rather than variable) value, and its influences on the optimisation of productivity and fuel efficiency have rarely been the focus of research within the field. In this research, its influences were tested along with various RPM settings based on industrial standard technical specifications from the International Organization for Standardization (ISO), to determine the practical and scientific importance of BCD to both industry and academia.

## 2. The determinants of excavator productivity

A general definition of productivity is given by the association of input(s) and output(s) in the particular context, i.e. productivity = output/input, and this is the common formula adopted within the industry (Park, 2006). In the context of excavators, output has often been quantified in terms of the materials handled by machines; e.g. volume of spoil moved per operator-hour (Elazouni and Basha, 1996), or volumetric capacity of the bucket (Solazzi, 2010). This simplistic interpretation has been explored and expanded in various research projects reported in the literature and in practice, so this section explores some of the key factors that appear to determine the productivity of hydraulic excavators.

As stated in the International Organisation for Standardization's Technical Specification 11,152, earth-moving machinery – energy use test methods (ISO/TS 11,152), cycle time is defined as the amount of time it takes a machine to perform a repetitive segment of an operation, typically measured as the time it takes a machine to return to the same position (ISO, 2012). The fastest achievable cycle time of an excavator is arguably the most meaningful indicator of machine productivity for a given duty, but prediction is difficult and results may therefore be inaccurate. First, in a study of observed performance of construction equipment working in Egypt, Elazouni (Elazouni and Basha, 1996) concluded that two groups of issues affect productivity, i.e. identifiable or undetectable factors. The former are detectable before the duty starts and thus a planner could plan ahead to counteract the effects that may have a negative impact on productivity (e.g. soil/ground conditions, work-space restrictions and hauling distance). In contrast, undetectable factors do not emerge until the duty has commenced (e.g. weather conditions, site management effectiveness and downtime) (Elazouni and Basha, 1996). Cycle time (in seconds) was considered to be an important unit in the measurement of productivity factors, but to fully account for these factors, a performance ability ratio (PAR) value was introduced, which is the ratio of the predicted productivity to the actual productivity, in order to judge the effect of the operator on productivity (Alfeld, 1988).

An alternative approach, based on data from machine performance handbooks from OEMs, was taken by Edwards and Holt (Edwards and Holt, 2000), who developed a productivity prediction model, ESTIVATE, which estimates excavation cost, based on the given cycle time (cycle/h) and productivity (m<sup>3</sup>/h) of the excavator. Unlike the model of Elazouni (Elazouni and Basha, 1996), the cycle times were derived from OEM performance handbooks (notwithstanding criticisms of the accuracy of such

data) (Lambropoulos et al., 1996), and a multiple regression equation was used.

$$Y = \beta_0 + \beta_1 x_1 + \dots + \beta_n x_n \quad (1)$$

$Y$  is the cycle time under the influence of  $\beta$

$\beta$  is the partial regression coefficient, which varies with  $x$

$x$  is the particular independent variable

Based on previous work (Edwards and Holt, 2000) and evidence from OEM performance handbooks to support the significant relationship that these variables have with cycle time, three independent variables ( $x$ ) were selected (machine slew angle, digging depth and machine weight) to model the dependent variable, cycle time ( $Y$ ). Two further variables, excavation materials and site obstructions, were also used to estimate the maximum and minimum cycle times.

The effect of bucket capacity is also commonly considered in research on excavator productivity (Schabowicz and Hola, 2007). Panas and Pantouvakis (Panas and Pantouvakis, 2010) identified a number of operational coefficients, such as dig depth, slew angles, bucket capacity and machine weight and used data from a construction site to develop a cost prediction system. Interestingly, this included a value for the power requirement by the excavator to overcome the resistance of the dig (Lambropoulos et al., 1996), but understanding the optimum relationship between bucket characteristics and output is difficult. Different rated bucket capacity (heaped) definitions can affect the estimation of the total volume of material being collected by the same bucket. This is critical, as international standards, such as SAE (Society of Automotive Engineers), SAE J2754-2007 and BS (British Standard), BS 6422:1983, as shown in Fig. 1, examples of various industrial standards definitions of heaped angles, have defined the angles differently and these have since been adopted within different countries. In the research reported in this paper BS 6422:1983 has been adopted.

Although some think that it is good for productivity if peak volumetric fill is always achieved, others disagree, suggesting that to minimise cycle time operators tend to fill the bucket to only 80% of capacity which results in more passes than would be required if the bucket was always filled to 100% (Fiscor, 2007). Spinelli et al. (2009) points to the “Piece-Size Law” to show that productivity increases at a decreasing rate with the increase of the piece size, up

to the optimum (Spinelli et al., 2009). Yet as piece size increases beyond the optimum, productivity will fall as the demand on the machine will increase due to the weight of the load. The productivity value therefore exhibits a parabolic behaviour against piece size ( $m^3$ ), see Fig. 2, the piece-size law. However, the graph assumes maximum engine and pump output, and overlooks additional fuel consumed as a result, so this approach is arguably flawed in both cost and environmental terms.

Indeed, fuel efficiency is the third and final point to cover here. Elton and Book (2010) defined fuel efficiency as a measure of how much fuel a machine uses to complete a certain task, which can be treated as a way to measure task efficiency (Elton and Book, 2010). Task efficiency is the measure of input required to achieve a particular amount of output. In this experiment, task efficiency is measured as the amount of soil moved per unit of fuel ( $kg/l$ ) (Elton and Book, 2011).

Fuel consumption of a diesel engine is determined mainly by engine torque and RPM settings at a given time, a certain amount of fuel is injected into the combustion chamber for combustion, hence the higher the RPM setting is the greater the amount of fuel that will be consumed. The Department for Environment Food & Rural Affairs (DEFRA) stated that every litre of diesel fuel combusted will produce 2.67  $kg\ CO_2e$  GHG emission, hence the more fuel consumed the more GHG emission will be produced. Fig. 3 shows an example of an engine fuel map (Miller, 2010); note that the lowest RPM does not necessarily give the lowest fuel consumption. RPM is often set to its maximum level and changes rarely throughout jobs, as high RPM will speed the machine up, complete the job more quickly and provide sufficient hydraulic power for most duties, however more fuel will be burnt as a result.

Under the Companies Act 2006 (Strategic Report and Directors' Report) Regulations 2013, UK companies are required to report their GHG emissions. DEFRA have derived GHG conversion factors to quantify GHG emissions such as  $CO_2$  ( $kg\ CO_2e/litre$ ),  $CH_4$  ( $kg\ CO_2e/litre$ ) and  $N_2O$  ( $kg\ CO_2e/litre$ ) produced from combusting various fuel types (Hill et al., 2012).

Gazi et al. (2012) claims that the environmental impact of GHG that is generated by diesel fuel, with the exception of  $CO_2$ , is less than 1% of the total amount of GHG generated. The total  $CO_2$  emissions of a certain amount of work done can be found by (Gazi et al., 2012):

$$CO_{2emission} = E_{CO_2} \times (3600 \times n_{th} \times E_{con}/p \times LHV) \quad (2)$$

( $E_{CO_2}$ ) is the diesel combustion  $CO_2$  emission factor

( $n_{th}$ ) is the thermal efficiency of machine

( $E_{con}$ ) is the energy consumption over certain work done ( $kWh$ )

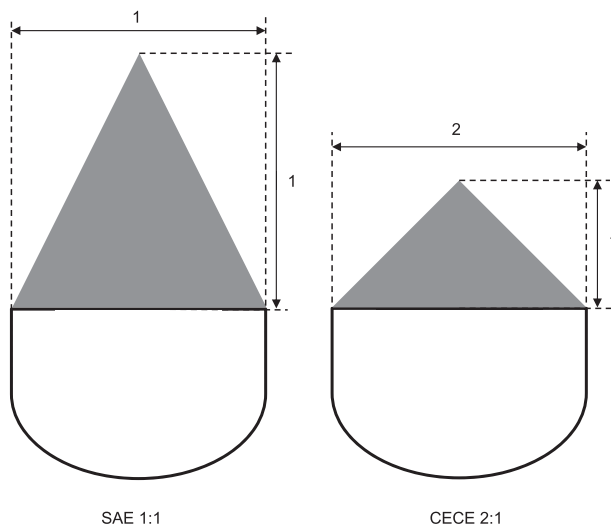


Fig. 1. Examples of various industrial standards definitions on heaped angles.

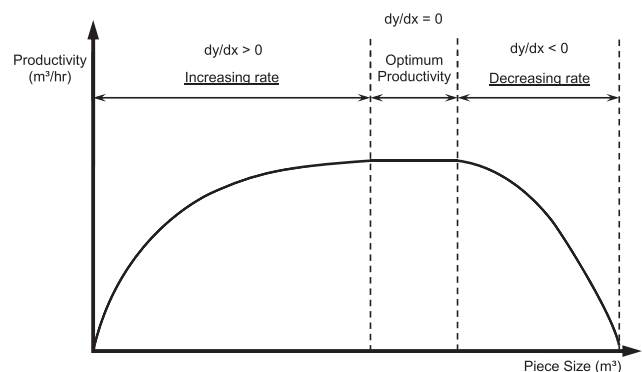


Fig. 2. The piece-size law.

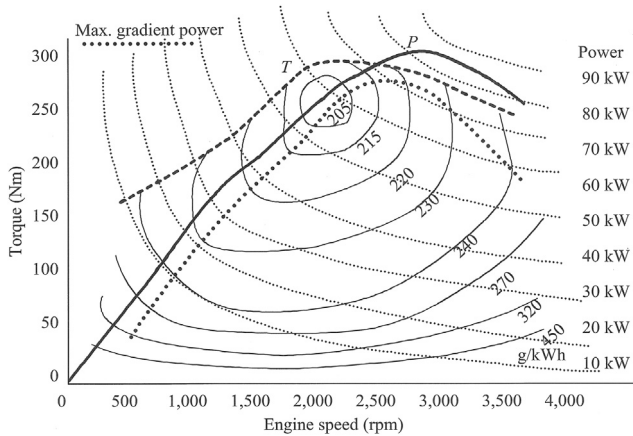


Fig. 3. Engine fuel map.

(P) is the density of diesel fuel ( $\text{kg}/\text{m}^3$ )

(LHV) is the lower heating value of diesel fuel ( $\text{kJ}/\text{kg}$ )

As stated in Fig. 3, engine fuel map, engine torque has a direct influence on how much fuel is consumed. The engine torque value can vary dramatically for an excavator when performing any particular duty. This is due to the excavatability of the materials being extracted, i.e. the resistance force being exerted on the bucket at a given time. The hydraulic pumps will need to provide varying degrees of hydraulic fluid volumetric flows and pressure to the rams to generate the necessary force to extend and retract the bucket, dipper arm and the boom against a given load, hence torque can vary. The highest pressure experienced during a trenching duty is when the bucket is forced into the ground, dragged towards the machine and breaks through the surface (Ng, 2012), as shown in Fig. 4, engine torque behaviour during trenching. As the pump is working harder to generate the pressure that is needed, the engine will equally need to consume more fuel to generate the torque in order to support the pump.

### 3. How the OEM industry determines productivity

Having identified some key determinants of excavator productivity and overviewed the nature of the relationships between

them, it is now pertinent to consider how OEMs interpret these parameters and communicate what they see as optimum fuel saving productivity to their customers and operators. Some industry bodies have attempted to model excavator productivity, and thus synthesise the factors described in the previous section. For instance, in 1983, the Central Association of the German Building Sector (Zentralverband des Deutschen Baugewerbes) and the German Federation of the Construction Industry (Hauptverband der Deutschen Bauindustrie) published the BML handbook (Handbuch BML: Daten für die Berechnung von Baumaschinen-Leistungen) (Zentralverband des Deutschen Baugewerbes (Central Association of the German Building Sector), Hauptverband der Deutschen Bauindustrie (German Federation of the Construction Industry), 1983), which suggests the following to calculate the hourly productivity of a fleet of excavators ( $Q_{\text{eff,BML}}^{\text{exc}}$ ), in units of ( $\text{m}^3/\text{h}$ ):

$$Q_{\text{eff,BML}}^{\text{exc}} = 60 \times n_{\text{exc}} \times \left( V_{\text{cece}} \times f_{\text{fill}} \right) / t_{\text{th,BML}}^{\text{exc}} \times f_{\text{swing}} \times f_{\text{depth}} \times f_{\text{E}} \quad (3)$$

( $n_{\text{exc}}$ ) [–] is the number of the excavators within the fleet

( $V_{\text{cece}}$ ) [ $\text{m}^3$ ] is the rated capacity (heaped), which dictates the height of the piled material. Different OEMs have adopted a standard defined by the Committee for European Construction Equipment (CECE), to determine heaped angle ratio, which dictates the height of the piled material as shown in Fig. 1, examples of various industrial standards definitions on heaped angles.

( $f_{\text{fill}}$ ) [–] is the coefficient which describes the actual volumetric coverage of the spoil to the buckets' nominal capacity.

( $t_{\text{th,x}}^{\text{exc}}$ ) [min] is the theoretical cycle time of a given excavator (this will vary according to engine size and weight), based on the bucket's nominal capacity, soil types and soil excavatability (Panas and Pantouvakis, 2010). The attributes that affect theoretical cycle time ( $f_{\text{swing}}$  and  $f_{\text{depth}}$ ) are considered separately.

( $f_{\text{swing}}$ ) [–] as applied in Equation (3), is the slew angle coefficient that describes the amount of rotation of a hydraulic excavator above the tracks or wheels, involved in a duty, as shown in Equation (4). Based on OEMs performance handbooks, it is accepted that the larger the slew angle is, the longer it will take the excavator to complete the task. BML specified two coefficients representing the fixed slew angles of  $45^\circ$  and  $180^\circ$ .

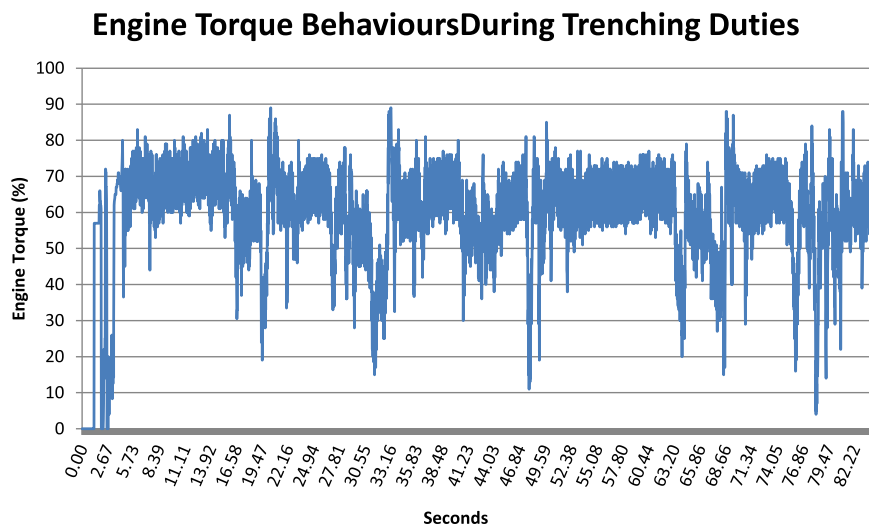


Fig. 4. Engine torque behaviour during trenching.



Similarly Komatsu Ltd. calculated a 3–6 s difference between the two slew coefficients (Komatsu Limited, 2009); Caterpillar Inc. quantified five sets of slew angles for their cycle time scale (Caterpillar Inc, 2011).

$$f_{\text{swing}} \approx 1.754 \times a^{-0.1258} \quad (a \in [45^\circ, 180^\circ]) \quad (4)$$

( $f_{\text{depth}}$ ) [–], digging depth coefficient describes a proportion of the maximum vertical distance that the bucket can reach below the horizontal line of the tracks/wheels. Here, excavatability is described in terms of the properties of the excavated material and the vertical distance ( $h_d$ ), the latter of which can affect productivity by 20% in extreme cases (Panas and Pantouvakis, 2010). OEMs often interpret ( $f_{\text{depth}}$ ) as a percentage.

( $f_E$ ) [min/min] is the efficiency coefficient. It is a factor that indicates the proportion of the hour that the excavator has worked. The factor is calculated by the following equation;

$$f_E = (60 \text{ minutes} - \text{Stoppage Time})/60 \text{ minutes} \quad (5)$$

Equation (3) is helpful, but in the intervening 30 years since its publication, most OEMs have used the above to derive their own, broadly similar, ways of quantifying excavator productivity. Equation (6) (Caterpillar Inc, 2011), Equation (7) (Komatsu Limited, 2009) and Equation (8) (J C Bamford Excavators Limited, 2007) are examples of productivity equations used by the leading global OEMs within the industry:

$$Q_{\text{eff,CAT}}^{\text{exc}} = 60 \times n_{\text{exc}} \times (V_{\text{cece}} \times f_{\text{fill}}) / (t_{\text{th,CAT}}^{\text{exc}} \times f_{\text{con}}) \times f_E \quad (6)$$

$$Q_{\text{eff,KOM}}^{\text{exc}} = 60 \times n_{\text{exc}} \times (V_{\text{SAE}} \times f_{\text{fill}}) / (t_{\text{th,KOM}}^{\text{exc}} \times f_{\text{con}}) \times f_E \quad (7)$$

$$Q_{\text{eff,JCB}}^{\text{exc}} = (V_{\text{SAE}} \times f_{\text{fill}} \times t_{\text{th,JCB}}^{\text{exc}} \times f_E) / f_{\text{con}} \quad (8)$$

The key difference between these equations and the BML Equation (3) (Zentralverband des Deutschen Baugewerbes (Central Association of the German Building Sector), Hauptverband der Deutschen Bauindustrie (German Federation of the Construction Industry), 1983) is that in Equations (6)–(8) a conversion coefficient ( $f_{\text{con}}$ ) has been included, however each OEMs defines their factor in a different manner:

- Caterpillar Inc. includes operator skill/efficiency coefficient and machine availability;
- Komatsu Ltd. includes a percentage of the actual dig depth against the maximum with the dump conditions; and,
- J C Bamford Ltd. includes a percentage of actual dig depth against the maximum with the swing angle.

#### 4. The relationship between fuel consumption and productivity

All of the above OEM equations for productivity and much of the related academic research essentially appear to be grounded in temporal (i.e. rate of excavation) and volumetric (i.e. bucket capacity) constructs. Exploration of other factors appears limited; for example only one of the equations above includes an explicit coefficient for operator behaviour. Moreover, most academic research in this area appears to have been conducted under the assumption that the machine will be set to perform at its maximum capability,

however, as explained earlier, under such conditions, more fuel will be consumed and GHG emissions will be generated at the peak rate, which in most cases will add unnecessary cost and emissions to the environment. Furthermore, overloading (or peaking out) the engine will only expose the engine and the structure to unnecessary stress, significantly decreasing components' life expectancy (Doosan Equipment, 2013) and therefore causing further strain on the environment. In addition, the majority of the extant literature on excavator productivity overlooks fuel efficiency as an important component in the perceived productivity of a machine, from the perspective of the operator. The cost of fuel is acknowledged as a concern in the industry (Agriculture and Horticulture Development Board, 2013), hence its omission also seems unwise.

In response to the above, it is therefore appropriate and timely to seek out ways to achieve cleaner productivity, and hence lower GHG emissions. Such an initiative would benefit the user, in terms of lower fuel costs, benefit hire companies, in terms of increased machine longevity, benefit the OEM, in terms of potential competitive advantage and benefit the environment in terms of reducing the total GHG emissions from NRMMS. The need for new methods to aid the selection of an appropriate machine for specific operational parameters has already been identified (Edwards et al., 2001), for example, minimising movement of the excavator and maximising the available tear-out forces (Singh, 1997), i.e. positioning of the excavator, positioning of the dump truck and digging technique. In previous sections, operators are often mentioned to be one of the main influences on productivity and fuel efficiency, and this claim has been further strengthened by the factors used within the productivity equations, such as  $f_{\text{swing}}$ ,  $f_{\text{depth}}$  etc. These factors are influenced by the operator, and are not controlled by most machine models available on the market, but operators are rarely a research focus for productivity or fuel efficiency improvement. Therefore, there is an incentive to create new ways of understanding that can be easily followed by the operators to achieve the optimal fuel efficiency and productivity.

Operators have always been the key to achieving high productivity and fuel efficiency for different duties. As a result, some OEMs are now offering training programmes to operators to enable them to use machines more efficiently. Most construction machines found working on site are hired by the contractors from a rental company and the contractor's aim will be to complete the job quickly and cheaply (by minimising the fuel and hiring period cost). Therefore some contractors are more willing to hire trained operators in order to reduce total costs. As stated in the Sustainability report in Rental Industry from the European Rental Association, an average of 10%–15% savings on fuel cost can be achieved as a result of these programmes (Aldeano et al., 2012). Volvo Construction Equipment Division states that a well-trained operator can potentially achieve a 5%–25% fuel reduction by adopting an environmentally friendly operating style, such as not over working the engine, without reducing their productivity level (Volvo Construction Equipment Press Information, 2010). Komatsu claims a 23% fuel saving can be achieved by just lowering engine power by 25%. Despite this change, fuel efficiency increases by 14%, which is equivalent to a 23% decrease in fuel consumption as a result, however productivity and cycle time suffered a 12% and 11% decrease respectively (Komatsu Limited, 2009). Hence, although these reports do support the claim that lower fuel consumption results from lower engine speed, the relationship with productivity levels is less well understood.

Based on the previous discussions on key variables related to excavator productivity, the focus of this research is to explore how to jointly improve both fuel efficiency and productivity in hydraulic excavators. An investigation has been conducted to test whether RPM and a new variable, bucket cut depth (BCD – see explanation

in following section) have a direct effect on fuel efficiency and productivity of an excavator. The results provide the underpinning performance data for operators to learn how to reduce fuel consumption, whilst maximising productivity, using RPM and BCD as independent variables.

This research aims to answer the following question with a view to developing a better understanding of the variables involved:

#### 4.1. Do RPM and BCD (as independent variables) have a direct effect on both productivity and fuel efficiency on a hydraulic excavator?

In order to answer this question, the following research objectives were identified and explored under controlled conditions (as explained in the following section):

- 1.) To investigate the relationship between RPM, fuel efficiency and productivity.
- 2.) To investigate the relationship between BCD, fuel efficiency and productivity.
- 3.) To interrogate the above results and develop a productivity map for a hydraulic excavator under a given set of circumstances.

### 5. Experimental design

The core parameters and procedures for the experiments conducted in this research were selected in accordance to ISO/TS 11,152, earth-moving machinery – energy use test methods. Most of the variables discussed in Sections 2,3 and 4 for measuring productivity and fuel efficiency will be used. New variables were introduced based on the recommendations stated in previous sections, and detailed explanations can be found in this section. The control of these variables, e.g. swing angle, to ISO standards is extremely important as not only can it affect the outcome of the findings, but it is also essential to ensure the integrity of both the commercial and scientific results provided by this research.

One of the most common duties for excavators was selected, in which spoil has been excavated and placed into a 16 tonnes dump truck. A total of 16 sets of experiments (each of 10 cycles, as determined by the size of the dump truck) were conducted by an experienced operator (with over 25 years of experience), using a 22 tonne class excavator, in the same location and material conditions. Spoil was collected in the dump truck and weighed to quantify the amount of spoil collected by volume and weight. At the end of each 10th cycle, all conditions were reset for the next set of experiments. Each set of experiments was carried out using a different combination of the independent variables. Each set of the experiments was repeated once to obtain an average and to ensure the accuracy of the result. Dependent variables were collected with a stopwatch; videos of the duty were recorded for data validation purposes. Extracted materials were loaded into a dump truck and weighed using calibrated weight pads. Care has been taken that all the experiments were carried out with academic rigour and also, to ensure the findings are suitable for use within commercial contexts, the experiments have been conducted in accordance with ISO/TS 11,152.

#### 5.1. Independent variables (RPM and BCD)

To address the issue of buckets being utilised at less than 100% capacity to achieve shorter cycle times (Fiscor, 2007) and to establish whether maximising the bucket capacity in each dig does or does not have a positive effect on productivity ( $\text{m}^3/\text{h}$ ), a new factor is introduced here, i.e. bucket cut depth (BCD). This is not the same as ( $f_{\text{depth}}$ ), mentioned previously.

As shown in Fig. 5, side view of a construction bucket, BCD is given as a percentage, between 0% when the bucket is skimming on top of the surface (also known as grading) and 100%, when the bucket is fully dug in. In this case, two cut depths were used, 50% and 100%; the 50% BCD will be described hereafter as BCD<sub>50</sub>, and the 100% will be shown as BCD<sub>100</sub>. Both values are used currently in the industry, with 100% being the more common. Furthermore, to ensure that the results reflect only BCD's effects, all other factors shown in Equation (3) had to be controlled and fixed. Hence:

- ( $n_{\text{exc}}$ ) is constant, as the same machine was used throughout the experiment;
- ( $V_{\text{CECE}}$ ) is constant, as the same bucket was used (a general purpose bucket, measuring 1500 mm wide, with 1.19  $\text{m}^3$  capacity);
- ( $f_{\text{fill}}$ ) is constant, as the same material was used throughout the experiment; based on the material properties used, the fill factor should remain between 95% and 110%. The same operator was asked to perform the same duty with the same machine therefore the theoretical cycle time should also remain constant.

Four sets of RPMs were used, based on the findings from previous experimental results (Ng, 2012).

#### 5.2. Dependent variables (cycle time, fuel consumption and output)

Cycle time is a basic metric for loading performance, measuring the time taken for an amount of spoil to be moved into a dump truck, by an excavator. The cycle time is defined as the time taken from the start of one cycle to the start of the next (Hall, 2003). The total cycle time for ten cycles was recorded for each RPM setting and BCD.

Fuel consumption is the amount of fuel used, in litres (l), to conduct the required duties within the specific time span. It was measured by an external mechanical fuel meter (JPS engineering FMS 4, 12DC volt.), which is classified as a direct method for fuel flow measurement in ISO/TS 11,152. The fuel consumption was also measured by on-board fuel sensors, taking readings at every 1 s and broadcast onto the excavator's on-board CAN bus network.

Output is the amount of material that is moved within a specific number of cycles, measured in kilograms. The material was loaded into a dump truck and weighed at the end of each 10th cycle.

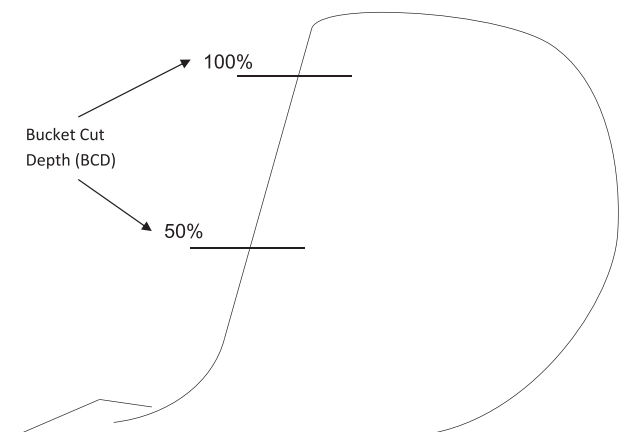


Fig. 5. Side view of a construction bucket.

### 5.3. Controlled factors (materials, swing and others)

To ensure the repeatability of the experiment, additional parameters were set as constants. Loose dry sand (Caterpillar Inc, 2011) stored in outdoor conditions was used and all experiments were conducted in similar weather conditions to ensure the composition of the material remained within an acceptable tolerance.

The angle of slew was set to 90°, and the excavator slewed only to load material into the dump truck and then returned to the dig area. Other factors such as the excavator, the dump truck, weight pads, operator, hydraulic system temperature, hydraulic oil levels, engine oil levels, digging style and data collection method remained the same throughout.

Further details about the experimental design:

- Swing angle: set to 90° with a tolerance of  $\pm 5^\circ$ ; this is due to the nature of loading a dump truck, and is an acceptable practice.
- Dig depths: 100% BCD: 1.317 m, and 0.6585 m for 50% BCD, hence the minimum and maximum  $f_{\text{depth}}$  will be 10% and 20% respectively. Based on the definition of  $f_{\text{depth}}$ , no effect will be seen on productivity if the operator is achieving anything less than 40% of the maximum dig depth (Panas and Pantouvakis, 2010).
- Finally ( $f_E$ ), the efficiency coefficient, will remain as 1, i.e. based on the assumption that each cycle is 100% efficient.
- Therefore, based on the BML productivity formula (Zentralverband des Deutschen Baugewerbes (Central Association of the German Building Sector), Hauptverband der Deutschen Bauindustrie (German Federation of the Construction Industry), 1983) and performance data provided by the OEM, the maximum productivity of the excavator should range between 341.81 m<sup>3</sup>/h, and 395.78 m<sup>3</sup>/h.

## 6. Results and analysis

The findings presented here are based on results collected from the experiments conducted as described in Section 5. For commercial reasons, it not possible to present the raw data, therefore all results are expressed in terms of a percentage gain. This allows the authors to present and discuss the results without compromising consistency or revealing commercially sensitive data. Percentage gain is used widely in the industry to describe the amount of fuel saved in vehicles or machines, so this method is deemed to be acceptable.

Table 1 provides an example of how the collected results were recorded. It shows the averaged results of four engine RPM settings and two BCDs.

Some initial analyses can also be found in the table, whereby percentage values are used to clarify the differences between the results. For example, “Percentage gain overall” indicates the amount of gain as a percentage from the least desirable result collected. By selecting RPM as a constant variable, any clear variation in the results between the two BCDs can be observed. The last three values at the bottom of the table show the highest percentage gain among the eight values and the maximum percentage gain for each BCD across the range of RPM used in the experiment. Table 1 is representative of six similar tables that were created, i.e. for: fuel consumption (l), cycle time (s), output (kg), productivity (m<sup>3</sup>/h), fuel efficiency (m<sup>3</sup>/l) and fuel consumption rate (l/h). The following Sections describe the outcomes of the experiments.

### 6.1. Engine speed vs. productivity

Fig. 6, the combined effect of bucket dig depths (BCDs) and engine speeds on productivity, shows how the productivity values

**Table 1**  
Results table example.

Fuel Consumption (Litre)		Engine RPM			
		1500	1600	1700	1800
Bucket Cut Depth (BCD)		Seconds			
	BCD <sub>50</sub>	28	25	24	22
	BCD <sub>100</sub>	34	30	27	24
		Overall Percentage Gain			
	BCD <sub>50</sub>	17.65%	26.47%	29.41%	35.29%
	BCD <sub>100</sub>	0.00%	11.76%	20.59%	29.41%
		Percentage Gain of BCD <sub>50</sub>			
	BCD <sub>50</sub>	17.65%	16.67%	11.11%	8.33%
Max. percentage gain between					
Overall		35.29%	BCD <sub>50</sub>	21.43%	
			BCD <sub>100</sub>	29.41%	

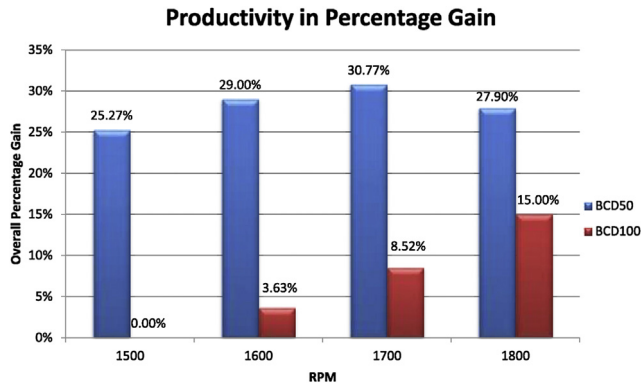


Fig. 6. The combined effect of bucket dig depths (BCDs) and engine speeds on productivity.

measured in  $\text{m}^3/\text{h}$  were generated due to the effect of the two BCDs and four RPM settings.

The four highest productivity values were all achieved by BCD<sub>50</sub> (50% cut depth), which showed a 25%–30% increase from the lowest recorded productivity achieved at 1500 RPM by BCD<sub>100</sub>. BCD<sub>100</sub> achieved a maximum 15% increase at 1800 RPM, and the pattern suggests that its gain would increase with higher RPM. Perhaps of greater significance is that BCD is clearly shown to influence productivity; there is only a 5% fluctuation in productivity rates across the RPM range of BCD<sub>50</sub>, whereas a much higher, 15%, fluctuation occurred for BCD<sub>100</sub> (100% fill level). These results indicate that a deep dig with higher RPM does not necessarily give the best productivity rates.

### 6.2. Fuel efficiency vs. engine speed

As mentioned earlier, fuel efficiency is a measure of how much spoil is removed per unit of fuel (kg/l). Fig. 7, the combined effect of bucket dig depths (BCDs) and engine speeds on fuel efficiency, shows the increases in fuel efficiency compared to the lowest recorded value in this data set, i.e. 1700 RPM for BCD<sub>100</sub>.

Similar to the findings in §6.1, the highest fuel efficiency values were achieved by BCD<sub>50</sub>. Results showed up to 23.5% less fuel consumed for every kg of spoil moved by BCD<sub>50</sub> at 1600 RPM. However, a much larger variance of 17% in fuel efficiency across the RPM range of BCD<sub>50</sub> can be observed. A gain of only 5% was observed with BCD<sub>100</sub> across the four RPM values. Based on this test, working at BCD<sub>50</sub> continuously shows benefits by reducing the amount of fuel required to complete the job, i.e. it uses less fuel to move a unit amount of material.

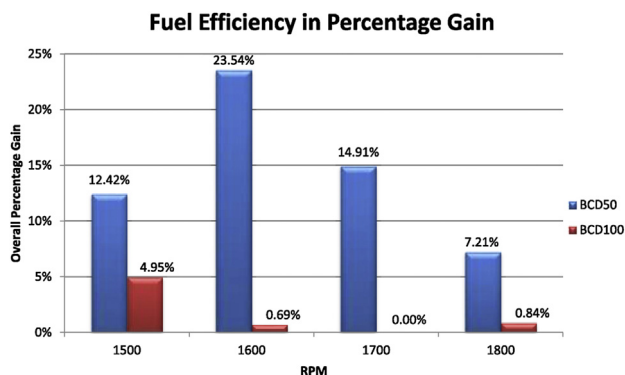


Fig. 7. The combined effect of bucket dig depths (BCDs) and engine speeds on fuel efficiency.

### 6.3. Fuel consumption rate vs. engine speed

Fuel consumption rate (l/h) is often used to measure the fuel efficiency and running cost of any products that are powered by a combustion engine. However this can be misleading. Indeed, Fig. 8, the combined effect of bucket dig depths (BCDs) and engine speeds on fuel consumption rate, shows that BCD<sub>100</sub> reduced its percentage gain as RPM settings increased, and shows that BCD<sub>100</sub> recorded the lowest fuel consumption rate. Although the rate is lower with BCD<sub>100</sub>, if given the time duration period, BCD<sub>50</sub> would have moved on average 30% more spoil with 26% saving on the cost of labour, machine rental costs and 25% of fuel cost.

If compared to the productivity value calculated earlier based on the productivity formula and data given by the OEM ( $341.81 \text{ m}^3/\text{h}$ , to  $395.78 \text{ m}^3/\text{h}$ ), the observed values were much lower, i.e. decreases of 19% and 28%, for BCD<sub>50</sub> and BCD<sub>100</sub> respectively.

### 6.4. Output vs. fuel use ( $\text{m}^3/\text{hl}$ )

Compared to the lowest performance, recorded by BCD<sub>100</sub> at 1600 RPM, Fig. 9, the combined effect of bucket dig depths (BCDs) and engine speeds on spoil moved per hour per litre, shows the percentage gain for amount of spoil moved per hour spent and litres of fuel consumed for the range of RPM used in this paper.

The graph clearly shows BCD<sub>50</sub> has a major advantage over BCD<sub>100</sub>. The data are shown in units of ( $\text{m}^3/\text{hl}$ ) which combines the importance of both productivity and fuel consumption into a single entity, hence achieving one of the aims of this paper. The results show that BCD<sub>50</sub> can increase the amount of spoil being moved by 40%–62.9% over BCD<sub>100</sub>. In industry terms, if a job is required to move  $10,000 \text{ m}^3$  of spoil, based on the current rate (in the web version) diesel price of £0.70 per litre (Agriculture and Horticulture Development Board, 2013), at a work site operating a 24 h shift, under such conditions if the right RPM and BCD were used, the operator would be able to achieve the same task using 24% less fuel, lower GHG emissions and 11 h faster, thereby saving £140 of fuel (at 2013 prices), without taking into account the savings from labour and machine rental costs.

### 6.5. (ProductivE+) – A map for cleaner productivity

The next stage is to visually present the data to clearly show the relationships between the independent variables (RPMs and BCDs) and the dependent variables (cycle time, fuel consumption and output). This has been done by combining the results into a map which in future will be referred to as the ProductivE + Map. The

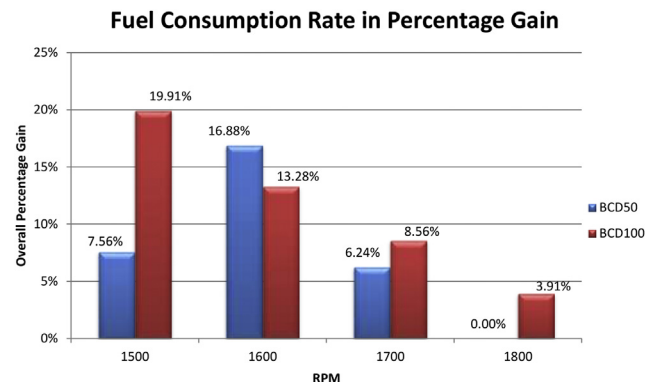
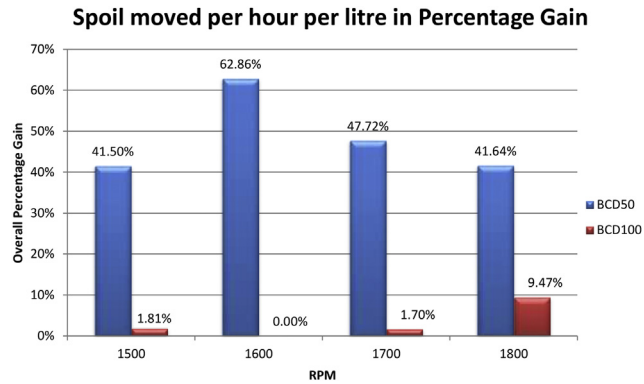


Fig. 8. The combined effect of bucket dig depths (BCDs) and engine speeds on fuel consumption rate.





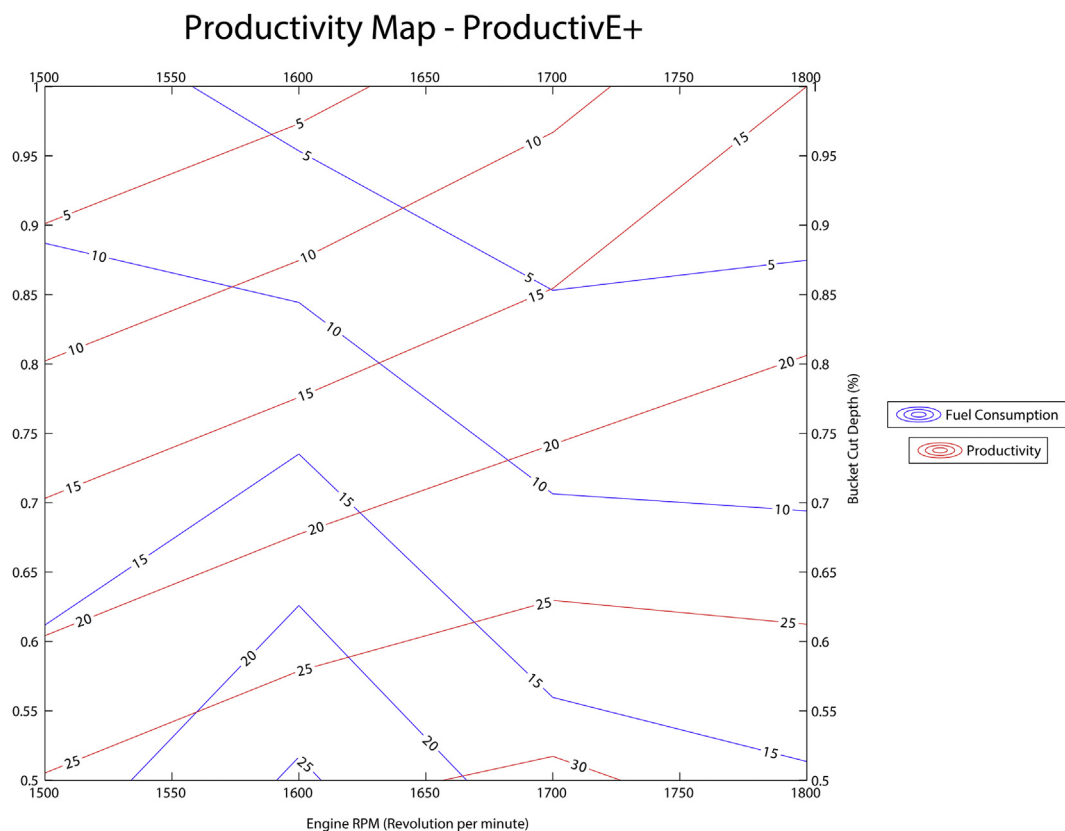
**Fig. 9.** The combined effect of bucket dig depths (BCDs) and engine speeds on spoil moved per hour per litre.

purpose of synthesising the data is to assist operators, in real-time, to understand that by limiting the machine end speed to a minimum they can cut down fuel consumption and GHG emissions, yet still increase productivity. Fig. 10, the ProductivE + map shows the data in a topographic format, demonstrating the effect of RPMs and BCDs on cycle time, fuel consumption and output.

To simplify the map, cycle time and output were combined into one unit: productivity ( $\text{m}^3/\text{h}$ , which is recognised by both industry and researchers). The fuel consumption pattern is laid over productivity to make clear the unexplored relationship between these variables. RPMs are on the x-axis, BCDs (%) on the y-axis and two variables, fuel consumption (litres) and productivity ( $\text{m}^3/\text{h}$ ), on the z-axis. The dependent variables are shown as a percentage gain in

5% intervals. Two different coloured lines in the map describe the behavioural pattern of the dependent variables. Fuel consumption (litres) is represented in blue (in the web version) and productivity ( $\text{m}^3/\text{h}$ ) in red.

The purpose of developing a full database from the ProductivE + map is to identify the maximum possible productivity and fuel efficiency of a particular excavator for a particular job and working environment. It is the first step towards the creation of guidelines on how to achieve cleaner productivity which can help operators in selecting the right RPM and use the correct BCD. As mentioned earlier, OEMs are pressured to offer operators more information to use the machine to achieve higher productivity at lower cost, the ProductivE + map will form a critical part of such information. Without the need to always rely on a low emission catalyst such as Diesel Exhaust Fluid (DEF) or technology such as diesel particulate filter (DPF), OEMs can configure their machines' fuel and engine speed management system by referencing the particular engine torque map. Aided by torque sensors in the engine, the speed can be automatically adjusted to lower fuel consumption and GHG emission. However results also show operator preference (in terms of BCD level) has a significant impact on productivity level, therefore the ProductivE + map does not only include the engine torque map but also guidelines for the operators to increase productivity and fuel efficiency by using the correct BCD levels. There are third party positioning systems on the market which monitor BCD levels, and such technology can be integrated with the ProductivE + map in order to assist the operators to achieve the highest fuel efficiency, without compromising productivity. ProductivE + can be used as a database to support an automated system built into the excavator. The system could then adjust engine speed and the bucket dig depth when excavating, and by default set the machine to



**Fig. 10.** The ProductivE + map.

1660 RPM and BCD to 50% to achieve the best possible productivity and fuel consumption rate. However, the operator should also be given the opportunity to use their judgement and experience and therefore should be given the option to shift the focus to either low fuel consumption or high productivity without compromising hugely on each other. This approach in using technologies for cleaner environmental impact offers multiple benefits in emission and cost savings, as mentioned in Section 6.4, and also in waste reduction, etc (Dovi et al., 2009).

However, the limitations of this research should also be noted. The results are valid for the particular parameters specified in Section 5 and the range of RPM and BCDs used was based on earlier experimental results, to locate the optimal machine setting for the particular working duty. If the ProductivE + map needs to be made compatible for the wider range of excavators, powered by different engines and hydraulic system configurations, more empirical measurements will be needed. Therefore, further work would be required to extend and create the required understanding of the behaviour of different excavators under different circumstances. Hence, other potential independent variables should be explored and a greater range of BCDs and RPMs settings should be tested. For example, different excavators and types of duties should be tested to create maps for different job tasks, although some of course may be common. Finally, the operator who participated in this experiment had more than 25 years of experience. As not all operators will exhibit the same level of experience or style, additional characterisations based on different operators' skill sets might also be considered.

## 7. Conclusion

While productivity is a well-researched area within operations research, a review of literature and industry guidance identified a gap in respect of fuel efficiency and productivity for hydraulic excavators. With concerns about fuel costs and a strong policy context invoking action towards reducing GHG emissions, there is growing concern that fuel consumption is not sufficiently reflected in physical and temporal measures of productivity. Moreover, the effect of operator behaviour on fuel consumption is often ignored or underestimated.

The relationship between fuel efficiency (kg/l) and productivity ( $\text{m}^3/\text{h}$ ) in excavators was scientifically investigated using two new independent variables, RPM and bucket cut depth (BCD) within an experimental environment. It has been found that BCD and RPM settings can affect fuel efficiency and productivity of the operation of a hydraulic excavator. In addition, the results over ruled the existing, common perception that the highest RPM setting will achieve highest productivity. Conversely, low RPM settings do not necessarily consume the least fuel to complete the same task. The results also scientifically prove that a half-filled bucket (50% BCD) can have a maximum effect of 30% improvement on productivity ( $\text{m}^3/\text{h}$ ), 24% saving on fuel efficiency (l/kg) and an overall amount of 62% more spoil moved per hour and litre of fuel consumed. The scientific results were further presented in a topographic map format and the ProductivE + data from this map could ultimately be used to identify the BCD and RPM required for a given excavator to undertake duties in the most fuel-efficient and productive manner.

This research responds to the need for companies to move towards cleaner productivity, by identifying an appropriate means to measure productivity and fuel efficiency as a single value. Operator training programmes should focus more on training the operators to select the correct engine speed and BCD, as an overarching strategy to improve productivity. The industry should use engine speed and BCD as variables to increase the accuracy of

productivity equations. ProductivE + can be converted into a database to support innovative technologies or features such as “smart” bucket or auto engine speed, to maximise the potential to serve the development of a novel, intelligent system to automate excavators to improve their fuel efficiency and cleaner productivity resulting in lower GHG emissions.

Further studies are required to focus on other construction machines such as backhoe loaders, telescopic handlers etc. Work is also required to improve the accuracy of the data, by including other applications with the same amount of work by different operators with various experience levels.

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