Predicting fuel energy consumption during earthworks

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1. Introduction

The construction industry's efforts to use resources more sustainably have mainly been directed towards building energy optimization (European Union, 2010) and the sustainability of construction materials (European Union, 2011). Only marginal interest has been shown in on-site resource management (i.e. energy, water and materials), because construction management has been mainly driven by decisions related to the maximum efficiency of operations, optimizing economic resources, timing, and the use of new technologies (Schaffhauser-Linzatti, 2012; Turkan et al., 2012; Zhang et al., 2013).

Previous research has mainly focused on the quantification and management of operating energy in buildings, while there has been less emphasis on embodied energy related to the construction process, namely on-site construction (Davies et al., 2013). A few studies have addressed the sustainability of the construction process. They demonstrated the existence and importance of the on-site environmental impact of construction projects, and developed criteria, methods and models for identifying and assessing this impact (Fuertes et al., 2013; Gangolells et al., 2009, 2011; Magnusson et al., 2015; Šelih, 2007; Shen et al., 2011; Zhao et al., 2006). However, none of these studies focused on the prediction of earthworks fuel consumption before the execution phase of the construction process.

Other studies (Chau and Muttil, 2007; Muttil and Chau, 2006, 2007; Wu and Chau, 2006) tackled sustainability by proposing statistical and mathematical methods for analyzing data related to pollution issues, but they did not propose an innovative, simple method for predicting earthworks fuel consumption during the planning phase of new residential construction projects.

Energy consumption due to on-site construction activity is also commonly ignored in life cycle assessment (LCA) studies, owing to a lack of available data and the inconsistent use of LCA boundaries (Davies et al., 2013). In other cases, it is simply approximated because the analysis is very complicated or the impacts are thought to be small (Guggemos and Horvath, 2006). The environmental impact of infrastructure and construction may be much lower than

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the impact of a building's operation. However, when we examine these environmental impacts in a different time frame, or as a function of all buildings, they may be considerable (Sharrard et al., 2008). In general, the construction phase has been found to contribute to 0.4–12.0% of the environmental impact. This figure is low due to the overwhelming impact of the use phase, which is much longer (Davies et al., 2013; Guggemos and Horvath, 2005; Junnila et al., 2006). According to Sharrard et al. (2007), on-site energy usage in the United States construction sector represents 2.6–3.0% of the entire US energy consumption, including passenger vehicles and shipping, while Ahn et al. (2010) report that consumption related to construction equipment use accounts for 0.8% of Canada's total energy consumption. However, these data underestimate the real consumption, since they do not include the use of on-road trucks.

Sharrard et al. (2007) indicate that gasoline and diesel fuel are responsible for the majority of energy consumption in the construction industry at 62–75% of all use, while electricity varies between 10 and 25% of the total energy consumption.

Substantial differences in the estimation of on-site fuel consumption in construction projects have been reported by Kotte (1996) and Peters and Manley (2012). Although construction equipment manufacturers provide power consumption information in their technical specifications, the challenge is that construction projects may involve complex and unique products and include a wide variety of construction techniques and systems (Gangolells et al., 2011). Thus, construction projects involve a great variety of tasks of variable duration, and the use of a range of equipment at different intensities. Other relevant factors are the distributed nature of construction and the subcontracting of activities (Sharrard et al., 2007). A lack of data on subcontractor fuel consumption (Peters and Manley, 2012) and a lack of data verification (Davies et al., 2013) are also highlighted as difficulties in the quantification of on-site energy consumption. Similarly, Kenley and Harfield (2011) stated that methods for measuring carbon dioxide and other greenhouse gas emissions in construction processes have yet to be developed, and Barandica et al. (2013) confirmed that statistics are needed on the fuel consumption of specific machinery.

Several authors have agreed that emissions generated by construction equipment are the main source of on-site environmental impact. Consequently, it is important to mitigate this impact (Ahn et al., 2009; Barandica et al., 2013; Carmichael et al., 2012; Frey et al., 2010; Kaboli and Carmichael, 2012). Ahn et al. (2009) pro-posed a method that integrates the emission model of construction vehicles with the simulation model of construction operations. However, the approach did not use information from project documents. Other authors such as Frey et al. (2010) and Zarotti et al. (2009) focused on on-site fuel consumption. Frey et al. (2010) published a set of field data on non-road equipment, including engine attributes, representative duty cycles, and average fuel use and emission rates, while Zarotti et al. (2009) analyzed fuel consumption during the operating cycle of an excavator, while it was in use with a professional operator. However, only the operating cycle was taken into account in this study; on-site excavator movements and pauses with the engine running, which can take up to half a workday, were not considered. Other studies, such as those by Al-Hasan (2007), Shikata (2009) and Kecojevic and Komljenovic (2011), also focused on earthworks machinery and its operation in relation to fuel consumption and emissions. Kecojevic and Komljenovic (2011) analyzed the impact of engine load conditions on fuel consumption and the subsequent carbon dioxide emissions, with a specific focus on bulldozers. Along the same line, Shikata (2009) indicated that bulldozer fuel consumption is highly dependent on factors such as site geography, weather and the maintenance program. Some recommendations about operation methods were also provided. Al-Hasan (2007) studied the impact of outside temperature on fuel consumption. Thus, although previous research has focused on the development of methods for estimating the fuel consumption of construction equipment, a predictive model based on information contained in construction project documents is still lacking.

Therefore, the aim of this research was to develop an innovative predictive model to estimate in advance (during the planning stage) the on-site fuel consumption and corresponding carbon dioxide emissions arising from earthworks in residential construction projects, using information from project documents. A number of four construction activities were reviewed, along with their corresponding fuel consumption agents. As a result of this review, we decided to focus on earthworks and related fuel consumption agents, because of their high environmental impact. We then developed the proposed method through a careful and in-depth analysis of machines' parameters. Over a hundred pieces of equipment made by the best-known manufacturers were considered and classified into main types. Classification parameters, in particular engine load factors, were identified.

Following this introduction, the second section describes the method adopted in this research. Then, to illustrate a practical application of the model, a case study is reported in the third section. The third section discusses also the results obtained using the model, and compares them with data collected on-site. The fourth section reports the conclusions of this research and the fifth presents future research issues.

2. Method

The method used in this research included the following steps:

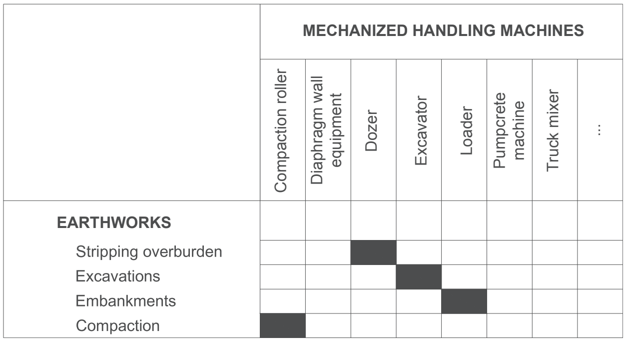
1. Identification of earthworks activities and corresponding fuel consumption agents
2. On-site fuel consumption analysis for earthworks activities
   2.1 Characterization of the fuel equipment
   2.2 Characterization of the load factor
3. Analysis of fuel consumption in transport
4. Estimation of on-site fuel consumption related to earthworks in building projects

2.1. Identification of earthworks activities and corresponding fuel consumption agents

In order to identify the fuel consumption related to each earthworks sub-activity, we used a process-oriented approach, similar to that applied by Gangolells et al. (2009). First, earthworks sub-activities were identified based on the Ente Nazionale Italiano di Unificazione UNI 8290-1 (Italian Company for Standardization, 1983), the Classification of Building Elements and Related Sitework of the American Society for Testing and Materials International (American ASTM, 2009), and the Spanish database from the Catalan Institute of Construction Technology (ITeC, 2013). The activities that were considered included: (1) stripping overburden, (2) excavations, (3) embankments and (4) compaction (Fig. 1).

Secondly, fuel consumption agents were identified, taking into account the Italian Joint Territorial Committee's list of equipment (Comitato Paritetico Territoriale, 2009). More than 100 pieces of equipment were considered and classified under the categories of (1) logistics services, (2) placed equipment, (3) aerial handling machines and (4) mechanized handling machines (Fig. 1).

As a result of this process, a list of earthworks sub-activities and corresponding fuel consumption agents were obtained. The agents included (1) dozers, (2) excavators, (3) loaders and (4) compaction



	MECHANIZED HANDLING MACHINES							
	Compaction roller	Diaphragm wall equipment	Dozer	Excavator	Loader	Pumpcrete machine	Truck mixer	...
EARTHWORKS								
Stripping overburden			■					
Excavations				■				
Embankments					■			
Compaction	■							

Fig. 1. Identification of on-site fuel energy consumption agents used during earthworks.

rollers, because these are the typical fuel equipment used during earthworks activities in new residential projects.

2.2. On-site fuel energy consumption analysis for earthworks activities

In order to evaluate the real fuel consumption of on-site equipment, a predictive model was developed taking into account the influence of diesel engine features and equipment operation. The fuel consumption required to perform 1 m^3 of any activity can be obtained using Equation (1), whereas the corresponding carbon dioxide emissions can be obtained applying Equation (2).

$$\text{Fuel consumption}_{\text{activity}}\left(\frac{\text{l}}{\text{m}^3}\right) = \sum_{i=1}^{i=n} \text{Fuel consumption}_i \cdot \text{Pr}_i \tag{1}$$

$$\text{Carbon dioxide emissions}_{\text{activity}}\left(\frac{\text{kg}}{\text{m}^3}\right) = \text{Fuel consumption}_{\text{activity}} \cdot \text{EF}_{\text{diesel}} \tag{2}$$

where Fuel consumption$_i$ is the fuel consumed by the equipment i expressed in l/h, Pr$_i$ represents the productivity of the equipment i expressed in h/m^3, and EF$_{\text{diesel}}$ represents the emission factor for diesel. According to the International Standard Organization (2012), the emission factor for diesel is assumed to be 2.60 kg of carbon dioxide per liter (following CO_2/l).

According to the Environmental Protection Agency (EPA, 2010), the fuel consumption of a given piece of equipment can be calculated as follows:

$$\text{Fuel consumption}_i\left(\frac{\text{l}}{\text{h}}\right) = P_i \cdot \text{SC}_i \cdot \text{LF}_{ij} \cdot \frac{1}{\rho_{\text{fuel}}} \tag{3}$$

where P_i represents the power of the equipment i expressed in kW, SC$_i$ is the specific consumption of the equipment i and depends on the engine's characteristic curve (expressed in kg/kW h), LF$_{ij}$ stands for the load factor of the equipment i and refers to the instantaneous loading of the engine in relation to its maximum capacity (expressed as a %) depending on the activity i and the soil layer j, and ρ_{fuel} denotes the specific weight of the fuel that ranges from 0.83 to 0.87 kg/l. According to Kecojevic and Komljenovic (2011), the average specific weight of the fuel is assumed to be 0.85 kg/l.

2.2.1. Characterization of the fuel equipment

Based on information in the technical specifications, the main equipment types and corresponding classification parameters were defined for each of the fuel consumption agents related to the earthworks activities: (1) dozers, (2) excavators, (3) loaders and (4) compaction rollers. We analyzed 38 models of dozers, and identified three types and three classification parameters for them (Table 1). Similarly, we analyzed 179 models of excavators, including 101 tracked excavators, 28 wheel excavators and 50 mini excavators, and identified five main types and five classification parameters within this category (Table 2). In the case of loaders, an analysis of 121 models, including 37 mini loaders, 75 wheel loaders and 9 truck loaders, allowed us to identify five main types and three classification parameters (Table 3). Finally, six main types and three classification parameters were identified within the main category of compaction rollers, through the analysis of 232 models, including 121 smooth drum rollers, 17 pneumatic rollers, 47 soil compactors and 47 tandem compactors (Table 4).

Then, specific consumption, measured in kg/kW h, was assigned to each type of equipment, according to the characteristic curves of the equipment's engine. When the specific consumption of a given piece of equipment could not be found because the engine's characteristic curve was not available, a value of 0.25 kg/kW h was assumed by calculating a rounded-up average of values found in the existing literature (Bocchi, 1987; South Coast Air Quality Management District, 1993; University of Nebraska-Lincoln, 2010; Picco, 2011).

Table 1
Characterization of dozers.

Type	Classification parameters			
	Operating weight [kg]	Blade width [m]	Maximum digging depth [m]	Power [kW]
Small dozer	8200–18,300	2.71–3.22	0.33–0.59	66.00–131.00
Medium-sized dozer	20,000–28,100	2.99–5.77	0.5–0.76	131.00–195.00
Big dozer	28,700–108,000	3.94–4.99	0.57–0.8	237.00–671.00

Table 2
Characterization of excavators.

Type	Classification parameters				
	Operating weight [kg]	Maximum digging depth [m]	Track width [m]	Bucket capacity [m^3]	Power [kW]
Mini tracked excavator	880–8400	1.13–4.15	0.73–2.99	0.02–1.05	6.80–48.5
Small tracked excavator	12,500–20,000	2.05–6.59	2.49–2.98	0.52–1.14	60.00–95.00
Medium-sized tracked excavator	20,200–35,400	6.00–14.91	2.38–3.19	0.40–2.66	95.00–200.00
Big tracked excavator	36,300–111,000	2.15–13.40	2.49–5.06	0.47–9.93	200.00–515.00
Wheel excavator	11,300–27,300	3.90–7.05	1.91–2.75	0.44–1.7	65.00–155.00

Table 3
Characterization of loaders.

Type	Classification parameters		
	Operating weight [kg]	Bucket capacity [m^3]	Power [kW]
Mini loader	5630–8450	0.23–1.80	52.00–71.00
Small wheel loader	5160–15,928	0.80–5.00	46.00–126.00
Medium-sized wheel loader	19,425–31,244	3.00–14.00	140.00–303.00
Big wheel loader	50,144–195,434	7.70–36.00	373.00–1092.00
Truck loader	3170–29,555	0.97–3.21	42.00–1176.00

Table 4
Characterization of compaction rollers.

Type	Classification parameters		
	Operating weight [kg]	Compaction width [m]	Power [kW]
Light smooth drum roller	2000–14,680	1.20–2.20	30.00–119.00
Heavy smooth drum roller	15,000–32,000	2.13–2.40	98.00–190.00
Pneumatic roller	8900–27,000	1.50–2.75	60.00–132.00
Soil compactor	7630–37,900	2.13–4.39	75.00–330.00
Vibratory soil compactor	5800–20,100	1.67–2.14	48.00–160.00
Tandem vibratory roller	6650–14,000	1.13–2.13	51.00–100.00

2.2.2. *Characterization of the load factor*

Typical load factors, understood as the average proportion of the equipment power that is actually used, were identified based on existing performance handbooks. Engine load factors depend on the machine model. Therefore, manufacturers' guides were analyzed to estimate the load factors and identify their qualitative variables. These documents usually provide three typical work application descriptions for each piece of equipment (named low, medium and high), and a load factor guide with a load factor range value based on the application description. We only considered qualitative variables related to construction project information in the documents. When the equipment load factor could not be found because performance handbooks were not available, a value of 59% was assumed (EPA, 2010). For the same reason, and because of limited empirical research, Ahn and Lee (2013) assumed a constant load factor for each piece of equipment.

In the following paragraphs, we present an in-depth analysis of the load factor for the main earthworks equipment. The main equipment and related types were chosen considering the typical organization of a medium-sized construction company and its fleet of machines. Dozers were excluded, because their activity is normally done by loaders. Thus, the items of equipment chosen were: medium-sized tracked excavator, small wheel loader, and vibratory soil compactor. For the medium-sized tracked excavator, we provide a detailed description of the method used to identify load factor values. For the vibratory soil compactor and small wheel loader we only provide a summary, since the method for deriving the load factors is similar for each equipment type.

2.2.2.1. Load factor for a medium-sized tracked excavator. For this type of equipment, the technical manuals that were consulted report that the load factor depends on two characteristic variables: the type of soil, and the duration of the daily work schedule. According to the Caterpillar Tractor Company (2012) and the Komatsu (2009), two main qualitative variables are significant in order to identify a homogeneous range of load factors (Table 5).

In this approach, as described in Gottfried (2013), Scesi and Papini (2006) and the Caterpillar Tractor Company (2012), the different types of soils were associated with a quantitative variable, represented by the corresponding material densities (considered in bank). The different types of soils were then clustered into three groups using a centroid-based clustering analysis method that assigns each density value to the closest centroid, based on a Euclidean distance measurement.

Fig. 2 represents the material densities that were identified, and the corresponding groups of load factor ranges: low, medium and high.

Having identified each material density in its proper range, a specific load factor was calculated for each material using a regression line of load factors, based on the ranges reported in the technical manuals.

Table 6 represents the final calculated load factor values, depending on material density.

At the end of this process, we had 24 load factor and material density values available. The relationship between the two variables was then estimated by a unique exponential regression line, as shown in Fig. 3 and reported in Equation (4).

$$\mathrm{LF}_1 = 0.0339e^{0.0014\cdot D} \tag{4}$$

where the dependent variable LF_1 represents the load factor (expressed as a %) and D stands for the material density expressed in kg/m^3. The coefficient of determination (R^2) was found to be 0.980 for values of material density within the domain [1370–2280 kg/m^3]. Based on the reported measurement error, the estimated equation shows good resilience.

Table 5
Identification of load factor ranges for a medium-sized tracked excavator, depending on type of soil and duration of use.

Load factor	Type of soil	Duration of use	Value
Low	Sandy soil and low density material	Digging less than 60% of the daily work schedule	20–40%
Medium	Clay soil and medium density material	Digging 60–85% of the daily work schedule	40–60%
High	Rocky soil and high density material	Digging more than 85% of the daily work schedule	60–80%

Source: Adapted from the Caterpillar Tractor Company (2012) and the Komatsu (2009).

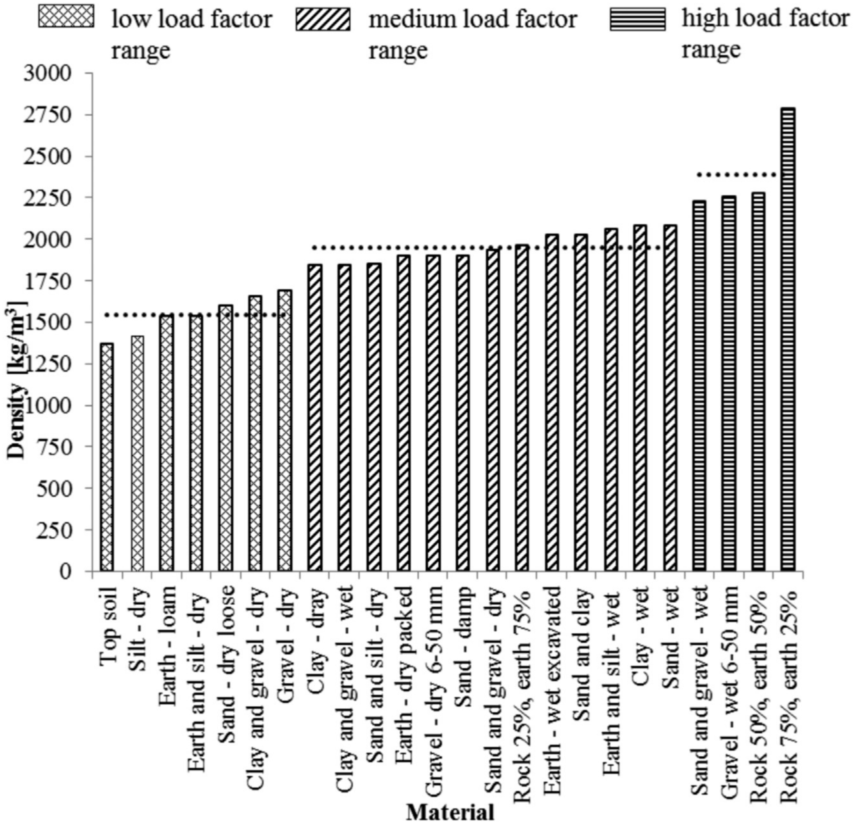


Fig. 2. Identification of load factor ranges according to the material density. The hatched line represents the cluster mean.

The same approach was used to identify the load factor, depending on the duration of use. First, a typical day's work schedule of 8 h was divided into increments of 10 min, from 0 min to 480 min. Taking into account Table 5, the corresponding percentage of the work schedule was associated with each value and with the corresponding load factor range (low, medium and high). Then, assuming a linear relationship between the duration of use and the load factor, a specific load factor was calculated for each duration of use value. There were 49 load factor values in total.

The relationship between the load factor and the duration of use is found to be represented by Fig. 4 and the corresponding Equation (5), with a coefficient of determination (R^2) of 0.987 for duration of use values within the domain [0–480 min]

Table 6
Identification of load factor values, depending on type of soil.

Type of soil	Material density in bank [kg/m^3]	Load factor range	Cluster mean	Load factor
Top soil	1370	L	1545.71	20%
Silt – dry	1420	L	1545.71	23%
Earth – loam	1540	L	1545.71	26%
Earth and silt – dry	1540	L	1545.71	29%
Sand – dry loose	1600	L	1545.71	31%
Clay and gravel – dry	1660	L	1545.71	34%
Gravel – dry	1690	L	1545.71	37%
Clay – dry	1840	M	1952.31	40%
Clay and gravel – wet	1840	M	1952.31	42%
Sand and silt – dry	1850	M	1952.31	43%
Earth – dry packed	1900	M	1952.31	45%
Gravel – dry 6–50 mm	1900	M	1952.31	47%
Sand – damp	1900	M	1952.31	48%
Sand and gravel – dry	1930	M	1952.31	50%
Rock 25%, earth 75%	1960	M	1952.31	52%
Earth – wet excavated	2020	M	1952.31	53%
Sand and clay	2020	M	1952.31	55%
Earth and silt – wet	2060	M	1952.31	57%
Clay – wet	2080	M	1952.31	58%
Sand – wet	2080	M	1952.31	60%
Sand and gravel – wet	2230	H	2390.00	65%
Gravel – wet 6–50 mm	2260	H	2390.00	70%
Rock 50%, earth 50%	2280	H	2390.00	75%
Rock 75%, earth 25%	2790	H	2390.00	80%

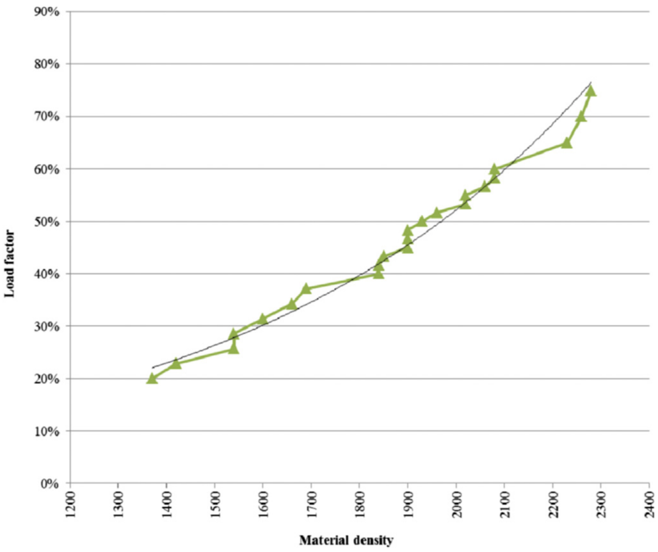


Fig. 3. Relationship between load factor and material density.

$$LF_2 = 0.2007e^{0.0262 \cdot T} \tag{5}$$

where the dependent variable LF_2 represents the load factor (expressed as a %), and the independent variable T stands for the duration of use expressed in minutes.

Therefore, the fuel consumption related to the excavation of 1 m^3 with a medium-sized tracked excavator can be obtained as follows:

$$\text{Fuel consumption}_{\text{excavation}}\left(\frac{1}{m^3}\right) = \sum_{i=1}^{n} P_i \cdot SC_i \cdot \frac{\frac{\sum_{j=1}^{n} W_j \cdot (LF_{ij1})}{\sum_{j=1}^{n} W_j} + LF_{i2}}{2} \cdot \frac{1}{\rho_{\text{fuel}}} \cdot Pr_i \tag{6}$$

where P_i represents the power of the equipment i expressed in kW, and SC_i is the specific consumption of the equipment i and depends on the engine's characteristic curve (expressed in kg/kW h). W_j is the indicator distinguishing each soil layer in relation to the prevalent material densities. W_j represents the mean thickness of the identified layers (m). LF_{ij1} is the load factor depending on the material density of each soil layer j and can be obtained by means of Equation (4), and LF_{i2} depends on the duration of use and can be obtained with Equation (5). Pr_i represents the productivity of the equipment i expressed in h/m^3, and ρ_{fuel} denotes the specific weight of the fuel.

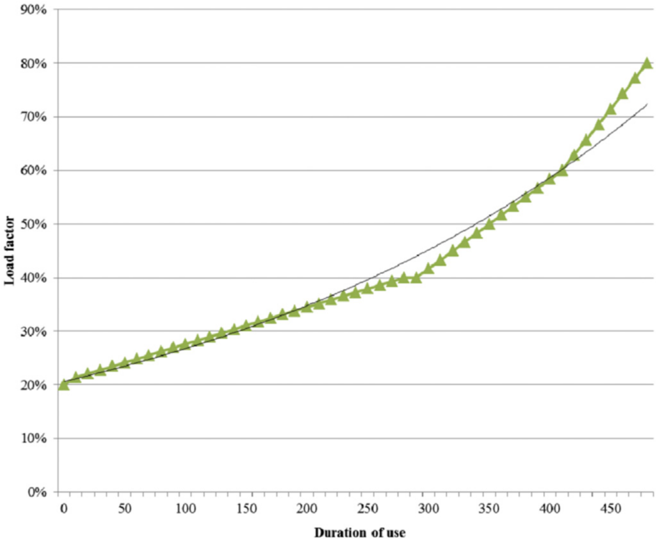


Fig. 4. Relationship between load factor and duration of use.

2.2.2.2. *Small wheel loader load factor.* For this type of equipment, the load factor depends on the type of soil, as in the case of excavators, and on the type of surface. Thus, according to the Caterpillar Tractor Company (2012), two quantitative variables were distinguished (Table 7).

We used the same method as for the excavator to calculate the load factors of specific small wheel loaders. As in the case of the excavators, different types of soils were associated with a quantitative variable, which was represented by the corresponding material densities (considered to be loose). For a total of 24 load factor values, the relationship between the load factor and the material density was found to be represented by Equation (7).

$$LF_1 = 0.05862e^{0.00101 \cdot D} \tag{7}$$

where the dependent variable LF_1 represents the load factor (expressed as a %), and D stands for the material density expressed in kg/m^3. The coefficient of determination (R^2) was found to be 0.984 for values of material density within the domain [950–2020 kg/m^3].

The same approach was used to identify the load factor, depending on the type of surface. Three different ranges of surface slopes were identified, taking into consideration Gottfried (2013): a grade of 0–10, a grade of 10–20, and a grade of 20–35. Taking into account Table 7, the corresponding load factor range (low, medium and high) was associated with each value. Then, a specific load factor was calculated for each grade value, to obtain a total of 36 load factor values.

The relationship between the load factor and the type of surface was found to be represented by Equation (8), with a coefficient of determination (R^2) of 0.991 for grade values within the domain [$0°$–$35°$].

$$LF_2 = 0.00868 \cdot G + 0.15333 \tag{8}$$

where the dependent variable LF_2 represents the load factor (expressed as a %) and the independent variable G stands for the grade of the slope.

Finally, the fuel consumption related to embankments of 1 m^3 with a small wheel loader can be obtained as follows:

$$\text{Fuel consumption}_{\text{embankments}}\left(\frac{1}{m^3}\right) = \sum_{i=1}^{n} P_i \cdot SC_i \cdot \frac{LF_1 + LF_2}{2} \cdot \frac{1}{\rho_{\text{fuel}}} \cdot Pr_i \tag{9}$$

where P_i represents the power of the equipment i expressed in kW, and SC_i is the specific consumption of the equipment i and depends on the engine's characteristic curve (expressed in kg/kW h). LF_1 is the load factor depending on the material density for each soil layer j and can be obtained by means of Equation (7), and LF_2 depends on the type of surface and can be obtained with Equation (8). Pr_i represents the productivity of the equipment i expressed in h/m^3, and ρ_{fuel} denotes the specific weight of the fuel.

Table 7
Identification of the load factor ranges for a medium-sized wheel loader, depending on type of soil and type of surface.

Load factor	Type of soil	Type of surface	Value
Low	Sandy soil and low density material	Smooth surfaces with minimal grade	15–25%
Medium	Clay soil and medium density material	Normal surfaces with slight adverse grade	25–35%
High	Rocky soil and high density material	Poor surfaces with adverse grade	35–45%

Source: Adapted from the Caterpillar Tractor Company (2012).

2.2.2.3. Vibratory soil compactor load factor. According to the Caterpillar Tractor Company (2012), the load factor of the vibratory soil compactor depends on the type of soil and the type of surface. Thus, two quantitative variables were distinguished (Table 8).

We proposed the same method as that used for previously analyzed equipment. As in the case of the loaders, the load factor range (low, medium and high) was defined for each material density, which was considered loose. With a total number of 24 load factor values, the relationship between the load factor and the material density is found to be represented by Equation (10).

$$\mathrm{LF}_1 = 0.05173e^{0.00142\cdot D} \tag{10}$$

where the dependent variable LF_1 represents the load factor (expressed as a %), and D stands for the material density expressed in $\mathrm{kg/m^3}$. The coefficient of determination (R^2) was found to be 0.992 for values of material density within the domain [950–2020 $\mathrm{kg/m^3}$].

The same approach was used to identify the load factor depending on the type of surface. Three different ranges of surface slopes were identified, considering the Caterpillar Tractor Company (2012) and Gottfried (2013): a grade of 0–3, a grade of 3–9 and a grade of 9–35. Taking into account Table 8, we associated the corresponding load factor range (low, medium and high) with each value. Then, a specific load factor was calculated for each grade value, and obtained a total of 36 load factor values.

The relationship between the load factor and the type of surface is found to be represented by Equation (11), with a coefficient of determination (R^2) of 0.995 for grade values within the domain [0°–35°].

$$\mathrm{LF}_2 = 0.21032\cdot G^{0.43210} \tag{11}$$

where the dependent variable LF_2 represents the load factor (expressed as a %), and the independent variable G stands for the grade of the slope.

Therefore, the fuel consumption related to the compaction of 1 $\mathrm{m^3}$ with a vibratory soil compactor can be obtained as follows:

$$\text{Fuel consumption}_{\text{compaction}}\left(\frac{\mathrm{l}}{\mathrm{m^3}}\right) = \sum_{i=1}^{n} P_i\cdot \mathrm{SC}_i\cdot\frac{\mathrm{LF}_1+\mathrm{LF}_2}{2}\cdot\frac{1}{\rho_{\text{fuel}}}\cdot\mathrm{Pr}_i \tag{12}$$

where P_i represents the power of the equipment i expressed in kW, and SC_i is the specific consumption of the equipment i and depends on the engine's characteristic curve (expressed in kg/kW h). LF_1 is the load factor depending on the material density of each soil layer j and can be obtained by means of Equation (10), and LF_2 depends on the type of surface and can be obtained with Equation (11). Pr_i represents the productivity of the equipment i expressed in $\mathrm{h/m^3}$, and ρ_{fuel} denotes the specific weight of the fuel.

2.3. *Transport fuel consumption analysis*

Along the same lines as Cabello Eras et al. (2013), the fuel consumed in the transport of excavated soil can be calculated as follows:

$$\text{Fuel consumption}_{\text{transport}}\left(\frac{\mathrm{l}}{\mathrm{m^3}}\right) = \sum_{i=1}^{i=n}\frac{K\cdot R_i\cdot \mathrm{Ic}_i}{C_i} \tag{13}$$

where K is the coefficient of the difference between the fuel consumption of an empty truck and a fully loaded one ($K = 1.7$), R_i is the mean distance traveled by each truck i from the construction site to the waste disposal area expressed in km, Ic_i represents the fuel consumption indicator of the fully loaded truck i expressed in l/km, and C_i is the capacity of the truck i expressed in $\mathrm{m^3}$.

As for fuel consumption agents of excavation activity, we defined the main truck types and the corresponding classification parameters on the basis of the information in the technical specifications. Five main types and three classification parameters were identified through the analysis of 83 models, including 63 on-road trucks, and 20 off-road trucks (Table 9).

2.4. *Estimation of the on-site fuel consumption related to earthworks in building projects*

The fuel consumption related to earthworks, expressed in $\mathrm{l/m^3}$ of excavated soil, can be obtained according to Equation (14), given below.

$$\begin{aligned}\text{Fuel consumption}_{\text{earthworks}} = {} & \text{Fuel consumption}_{\text{excavation}}\\ & + \text{Fuel consumption}_{\text{embankment}}\\ & + \text{Fuel consumption}_{\text{compaction}}\\ & + \text{Fuel consumption}_{\text{transport}}\end{aligned} \tag{14}$$

where $\text{Fuel consumption}_{\text{excavation,}}$ $\text{Fuel consumption}_{\text{embankments}}$ and $\text{Fuel consumption}_{\text{compaction}}$ represent the fuel consumed during excavation activities expressed in $\mathrm{l/m^3}$ of excavated soil, and Fuel

Table 8
Identification of the load factor ranges for a vibratory soil compactor, depending on the type of soil and type of surface.

Load factor	Type of soil	Type of surface	Value
Low	Soil not compacted to high density	Level ground, minimal slope	20–40%
Medium	Granular soil compacted to density	Working on slopes greater than 5%	40–60%
High	Cohesive soil with padded drum and high moisture content	Working on slopes greater than 15%	60–100%

Source: Adapted from the Caterpillar Tractor Company (2012).

Table 9
Characterization of trucks.

Type	Classification parameters		
	Operating weight [kg]	Speed at maximum power [km/h]	Power [kW]
Light on-road truck	3300–7000	126–184	70–150
Medium-sized on-road truck	6500–18,000	131.6–161.9	137–152
Heavy on-road truck	>16,000	81.9–117.1	228–560
Medium-sized off-road truck off-road	11,500–15,000	106.3–106.8	118–235
Heavy off-road truck	>16,000	66.9–113	265–534

$\text{consumption}_{\text{transport}}$ represents the fuel consumed during the transport of the excavated soil expressed in l/m^3.

In order to calculate the total project consumption, we need to know the volume of soil, and differentiate between the soil volume in bank that is excavated, and the loose soil volume that is used to fill a part of the dig, and then compacted or transported to the waste disposal area. Table 10 represents the different type of soils with the two material densities, the consequent % of soil expansion, and the material load factor. These values have been identified according to Scesi and Papini (2006), Gottfried (1995) and the Caterpillar Tractor Company (2012).

3. Case study and discussion of the results

The case study focuses on a new-start residential construction project located in Milan (Italy). The building has 8 aboveground floors and 3 underground floors, and a total floor area of 4786 m^2 (1792 m^2 aboveground and 2994 m^2 underground). The main construction work included the diaphragm walls needed to support the soil, excavations (total volume 11,415.76 m^3), embankments (total volume 294 m^3), a reinforced concrete structure (pillars and beams) and mixed slabs with joists and hollows for the aboveground floors. The underground floors were designed with pre-stressed predalles slabs. According to the project document “Budget”, the embankments were characterized by a total volume of soil of 294 m^3 divided into 5 different layers of about 20 cm of depth, while part of the excavated soil (11,121.76 m^3) was transported to an inert waste dump located 25 km from the construction site. The construction project document entitled “Geological study and geotechnical characterization of the foundation soils” described two prevalent soil layers: a dry, silty sand from 0 to 3 m deep, and a layer with compact and fine sand with gravel from 3 to 10 m deep. The soil layer, which was classified as top soil, was 1 m deep and was excavated and then embanked and compacted to create the logistics area outside the building area. The drawings for the construction project indicated that the excavation had a constant section. Figs. 5 and 6 represent the general drawing of the ground floor and a section of the building, respectively.

During earthworks and according to the health and safety plan, four types of equipment were planned to be used on-site, including two medium-sized tracked excavators with hydraulic shovels, one small wheel loader, one vibrator soil compactor and medium-sized on-road trucks. From the progress schedule of the general contractor works, the planned duration was found to be 780 days. According to the same document, excavations were planned to last 30 days, while embankment and compaction were planned to last 2 days. The duration of use of the medium-sized excavators was found to be the entire daily work schedule of the days planned for their activity (40 days). The duration of use of the small wheel loader was the entire daily work schedule on the days planned for its activity (2 days), which was the same duration of use as the vibratory soil compactor.

According to the Caterpillar Tractor Company (2012), the excavator productivity expressed in h/m^3 is 0.007 h/m^3 for excavator A, and 0.008 h/m^3 for excavator B, taking into account that the time considered is the equipment's average cycle time and a half,

Table 10
Characterization of soils.

Type of soil	Material density in bank [kg/m^3]	Material density loose [kg/m^3]	Soil expansion [%]	Material load factor
Clay – dry	1840	1480	24%	0.80
Clay – wet	2080	1660	25%	0.80
Clay and gravel – dry	1660	1420	17%	0.86
Clay and gravel – wet	1840	1540	19%	0.84
Earth – dry packed	1900	1510	26%	0.79
Earth – loam	1540	1250	23%	0.81
Earth – wet excavated	2020	1600	26%	0.79
Earth and silt – dry	1540	1245	24%	0.81
Earth and silt – wet	2060	1601	29%	0.78
Gravel – dry	1690	1510	12%	0.89
Gravel – dry 6–50 mm	1900	1690	12%	0.89
Gravel – wet 6–50 mm	2260	2020	12%	0.89
Rock 25%, earth 75%	1960	1570	25%	0.80
Rock 50%, earth 50%	2280	1720	33%	0.75
Rock 75%, earth 25%	2790	1960	42%	0.70
Sand – damp	1900	1690	12%	0.89
Sand – dry loose	1600	1420	13%	0.89
Sand – wet	2080	1840	13%	0.88
Sand and clay	2020	1600	26%	0.79
Sand and gravel – dry	1930	1720	12%	0.89
Sand and gravel – wet	2230	2020	10%	0.91
Sand and silt – dry	1850	1646	12%	0.89
Silt – dry	1420	1136	25%	0.80
Top soil	1370	950	44%	0.69

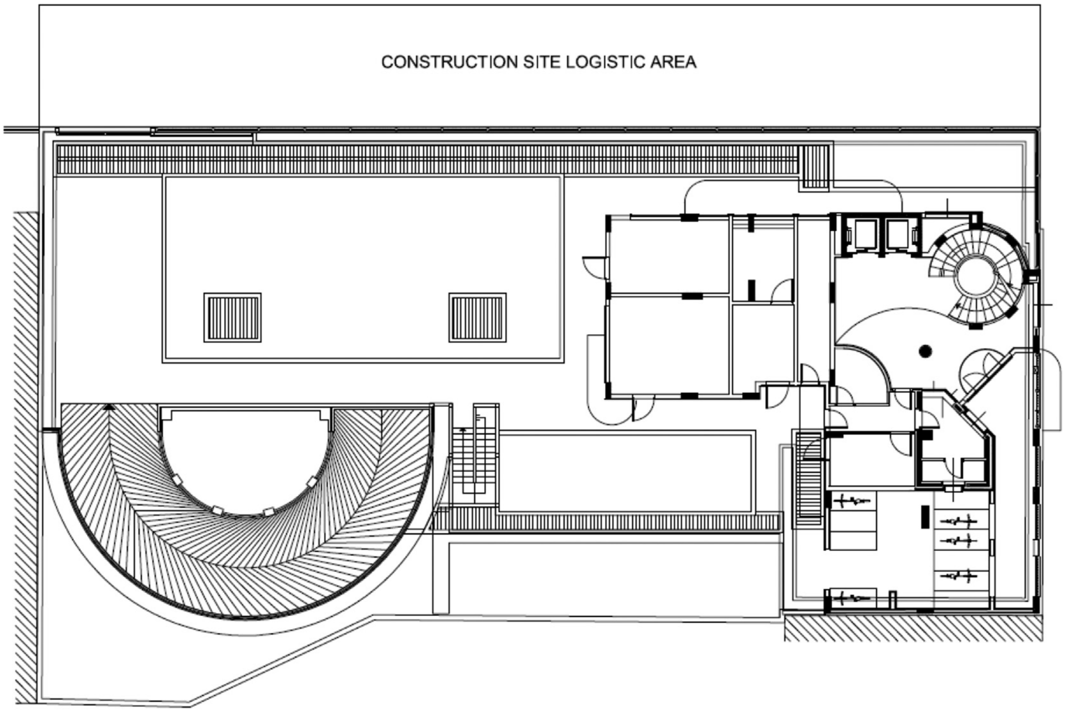


Fig. 5. General drawing of the ground floor of the building.

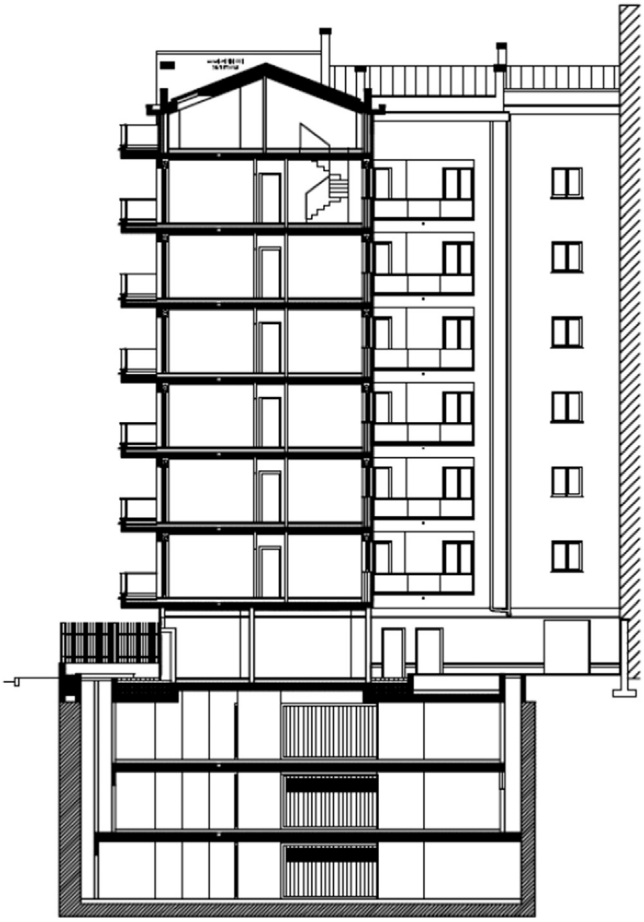


Fig. 6. Section of the building.

expressed in minutes, given for each machine size class from the Caterpillar Tractor Company (2012), and the equipment's heaped bucket capacity, expressed in m^3, is taken from the technical specifications. The bucket fill factor, expressed as a percentage that depends on the excavated soil materials in the case study, is 100% (Caterpillar Tractor Company, 2012). The job efficiency estimator for the case study, expressed as a percentage and considering the required breaks for operators (10 min per working hour), is 83%. To identify loader productivity expressed in h/m^3, we used the same equation as that for excavators (Caterpillar Tractor Company, 2012). A fill factor of 100% and an efficiency of 83% were considered. Finally, the loader productivity that was calculated is 0.008 h/m^3. According to the Caterpillar Tractor Company (2012), the vibratory soil compactor productivity expressed in h/m^3 is 0.012 h/m^3, taking into account that the number of machine passes to achieve compaction is assumed to be 6, the compacted width per pass expressed in meters of the equipment is 2.13 m as described in the technical specifications, the average speed expressed in kilometers per hour of the equipment is 3 km/h as described in the technical specifications, the compacted thickness of soil is 200 mm as determined in the project document “Budget” and the number of identified layers is 5, from the same document. Table 11 summarizes the main characteristics of the analyzed equipment.

Considering the excavation activity, and applying Equation (4), the load factor of the first layer (LF_1) was found to be 45%, whereas the load factor for the second layer (LF_1) was found to be 77%. When we applied Equation (5), the load factor (LF_2) was found to be 70%.

The excavation type was identified on the basis of the drawings in the architectural design. Excavation was found to be with a constant section, and W_j, represented by the thickness of the identified layers, were defined. W_j for the first layer with dry silty sand (0–3 m deep) was defined as 3, W_j for the second layer with compact and fine sand with gravel (3–10 m deep) was defined as 7.

We used Equation (6) to calculate the fuel consumption of the two medium-sized tracked excavators. The calculated fuel consumption was 0.194 l/m^3 for excavator A, and 0.189 l/m^3 for

Table 11
Main characteristics of the earthmoving equipment.

Equipment	Type	Operating weight [kg]	Power [kW]	Cycle time [min]	Heaped bucket capacity [m^3]	Productivity [h/m^3]
A	Medium-sized tracked excavator	28,700	140.00	0.38	1.10	0.007
B	Medium-sized tracked excavator	21,000	122.00	0.42	1.10	0.008
D	Small wheel loader	12,868	105.00	0.75	1.90	0.008
E	Vibratory soil compactor	10,555	98.00			0.012
F	Medium-sized on-road truck	12,500	137.00		20.00	

excavator B. Considering the duration of use of each excavator and the corresponding dug volume (data taken from the document "Construction site record"), the fuel consumption was found to be 2210.65 l for excavator A, and 1051.01 l for excavator B. The total project fuel consumption for excavations was found to be 3261.6 l, with a corresponding carbon dioxide emission of 8480.33 kg of CO_2.

Considering the embankment activity, we applied Equation (7) and found a load factor (LF_1) of 15% (top soil). When we applied Equation (8), the load factor (LF_2) was found to be 15% (0 grade). We used Equation (9) to calculate the fuel consumption of the small wheel loader, which was found to be 0.04 l/m^3. Considering the volume of soil, and data from the "Budget", the total fuel consumption for embankment in the project was found to be 10.80 l, with a corresponding carbon dioxide emission of 28.07 kg of CO_2.

Considering compaction activity, we applied Equation (10) and found a load factor (LF_1) of 20% (top soil). When we applied Equation (11), the load factor (LF_2) was found to be 20% (0 grade). Equation (12) was applied to calculate the fuel consumption of the compactor and we found a value of 0.07 l/m^3. The total project fuel consumption for compaction was found to be 19.86 l, with a corresponding carbon dioxide emission of 51.62 kg of CO_2.

We used Equation (13) to calculate the fuel consumption of the trucks. The mean distance (R_i) traveled by trucks from the construction site to the waste residue area, identified by the general-contractor in the project document "Budget", was found to be 25 km; while a truck capacity of about 20 m^3 was found in the technical specifications of the equipment. The volume of soil excavated that had been in bank and had to be transported to the waste disposal area was 11,121.76. Considering the soil expansion of the two prevalent identified layers (see Table 10), we calculated that the trucks would transport 3736.91 m^3 of dry silty sand soil and 8563.76 m^3 of compact and fine sand with gravel. Therefore, the value of fuel required to transport the soil was calculated as 7841.67 l, with a corresponding carbon dioxide emission of 20,388.35 kg of CO_2.

In conclusion, the total fuel consumption of earthworks activities caused by earthmoving equipment and trucks in the case study was calculated as 11,133.99 l, with a corresponding carbon dioxide emission of 28,948.37 kg of CO_2. Table 12 represents the final re-sults of fuel consumption and the corresponding carbon dioxide emission for earthmoving equipment in the case study.

We then compared predictive data and data from on-site monitoring and surveys. As observed during on-site inspections and confirmed by previous studies (Sharrard et al., 2007; Peters and Manley, 2012; Davies et al., 2013), reports or bills of fuel consumption are not available from the sub-contractors of earthworks activities. The standard behavior of construction companies is to use a tank truck that arrives on site to refuel equipment. Since the machines' tanks are not completely empty when the tank truck arrives, it is difficult to know the exact amount of fuel loaded into each piece of equipment, and thus records are not usually made. However, we carried out a survey by asking questions directly on-site to the equipment operators and the owner. According to this survey, the fuel consumption of the two excavators, the loader and the compactor, was as follows: about 140 l a day for excavator A, about 110 l a day for excavator B, about 30 l a day for loader C and the same amount for compactor D.

Considering the real working day of earthmoving machines reported in the "Construction site record" (18 days for excavator A, 11 days for excavator B, half a day for loader C and compactor D), the total fuel consumption was 3790.00 l. No user data were available on the fuel consumption of trucks. Thus, when we compared the predicted data (3292.31 l) with the actual data (3790.00 l), we found an underestimation of about 15% (actual data are higher). The reported error has several components: a typical model error derived from the assumption or mathematical techniques used, an observation error related to the methods used to register the validation data, and an exogenous error that depends on the other environmental conditions. It is reasonable to assume that the error is mainly due to the method used to collect validation data, because construction firms do not tend to indicate the hours of operation of machinery, but only their presence on-site expressed in days. Therefore, the time extrapolated from the "Construction site record" to calculate the actual consumption data is likely to be higher than the real figure. In fact, as stated in the Caterpillar Tractor Company (2012), a machine's work application can vary greatly. Periods spent at idle, dozer and pusher travel in reverse, haul units traveling empty, close maneuvering at part throttle, and operating downhill are examples of conditions that reduce the load factor. Therefore, this 15% represents a ceiling of potential model error. If we also consider that the weight of the other exogenous variables, such as operator temperament or attitude, may involve a 10–12% difference in consumption rates (Caterpillar Tractor Company, 2012), it can be stated that the proposed method is accurate enough and provides a reliable estimation of fuel consumption.

Subsequently, we compared the results with those from a literature review. Fuel consumption data for earthwork machinery

Table 12
Final results of fuel consumption and corresponding carbon dioxide emission for earthmoving equipment in the case study.

Equipment	Type	Fuel consumption [l/m^3]	Total fuel consumption [l]	Total CO_2 emission [kg]
A	Medium-sized tracked excavator	0.194	2210.65	5747.69
B	Medium-sized tracked excavator	0.189	1051.01	2732.64
C	Small wheel loader	0.04	10.80	28.07
D	Vibratory soil compactor	0.07	19.86	51.62
E	Medium-sized on-road truck	0.64	7841.67	20,388.35
Earthmoving equipment			11,133.99	28.948.37

reported by Cabello Eras et al. (2013), which ranged from 35.21 l/h to 23.7 l/h, show quite similar results. However, method with specific load factors considers each piece of equipment in a specific context, with the proper characteristics of the soil and the surface. A comparison of the results with those reported by Kecojevic and Komljenovic (2011) confirms that fuel consumption correlates strongly with the engine load factor.

Moreover, the calculated data were compared with those from a study by Zarotti et al. (2009). Zarotti used an auxiliary fuel circuit for consumption measurements and calculated 0.02684 kg/cycle of fuel for a medium-sized tracked excavator (i.e. 0.0315 l/cycle), which is 6.85 l/h. Considering productivity of 0.007 h/m^3, the fuel consumption was calculated as 0.05 l/m^3. This figure is quite different from that predicted with the proposed method (about 0.19 l/m^3). However, it must be taken into account that the first value tested by Zarotti et al. (2009) (0.05 l/m^3) exclusively relates to the operating cycle, without considering on-site excavator movements and pauses with the engine running. These movements and pauses may take up at least half of a workday, and were considered in the case study here (differences in duration of use). Secondly, the test trench in Zarotti et al. (2009) was about 1 m deep, while in the case study the digging depth varied from 0 to 10 m. Finally, the test carried out by Zarotti et al. (2009) used soft uncompacted soil, while the soil in the case study included a layer of dry silty sand (from 0 to 3 m deep) and a layer of compact, fine sand with gravel (from 3 to 10 m deep). Since there is a direct relationship between duration of use and the excavator load factor, the material density and the excavator load factor, and the indicator W_j represents the mean thickness of layers, then the duration of use, the material density and the digging depth explain the difference between the data obtained using the method in the case study, and the data obtained by Zarotti et al. (2009).

As a final consideration, both the predicted data and the actual data show that earthworks in new residential construction projects are a significant source of pollution. Therefore, they require careful analysis as they do in road projects, where one of the main sources of emissions is off-road machinery (Barandica et al., 2013).

4. Conclusions

A review of relevant literature on construction site fuel consumption assessment during the pre-construction stage revealed that no significant studies have been undertaken that address potential methods. In particular, no shared models have been proposed that are based on a detailed load factor parameter.

Therefore, we carried out a study that proposed a quantitative method to predict the on-site fuel consumption of earthworks activities during the pre-construction stage. First, the research identified fuel consumption agents related to earthworks activities. Then, an analysis of on-site fuel consumption was carried out by characterizing fuel equipment and load factors. Using data available from producers' technical manuals, and applying a cluster analysis method and then a linear regression, we calculated load factors for a medium-sized tracked excavator, a small wheel loader, and a vibratory soil compactor. An analysis of transport fuel consumption was also undertaken. We applied the method in a case study that demonstrated its practical use, and showed that the model's output behavior was sufficiently accurate.

Thus, the proposed method could be used by a construction designer (e.g. architect or engineer) who needs to make a simple comparison of design alternatives for residential construction projects and choose which one is more “sustainable” in terms of on-site fuel consumption. Then, the client can ask the contractor about predicted fuel consumption and use monitoring tools, such as meters, to check predictions.

The strength of this method lies in the fact that on-site fuel consumption is predicted in advance, based on information contained in the construction project's documents, so the design can be changed to minimize the impact. This is also useful within the framework of ISO 14004:2004, to identify and assess the magnitude of the environmental impact related to on-site fuel consumption.

Finally, in agreement with some previous studies, the research shows that earthworks are construction activities that have a great impact in terms of fuel consumption and consequent carbon dioxide emission. This highlights that we should not overlook on-site fuel consumption related to a new-start residential construction project and associated with the equipment used.

5. Further research

This research represents a first step towards predicting the on-site fuel energy consumption of a construction project. Further research is needed in this area. Construction processes are largely exposed to outdoor conditions, and this also affects fuel consumption. Some significant parameters related to outdoor conditions that can affect fuel consumption, such as temperature and moisture, should be investigated and eventually included in the proposed method. Other factors that could affect fuel consumption are related to the maintenance level of the equipment, which can have a negative impact on engine efficiency, and the workers' ability. Regular maintenance helps to conserve fuel, and lengthens machine life, while two operators with different temperaments or attitudes operating identical machines side-by-side in the same material can have as much as a 10–12% difference in consumption rates. Parameters related to outdoor conditions, maintenance and workers' ability could be included in the predictive model.

Further in-depth methodology developments are needed, through the involvement of earthmoving machines producers and their users, in particular earthworks sub-contractors. The comparison between predicted data and real data in several case studies could contribute to strongly validating the method. In fact, some machinery producers have specific fuel counters installed on their latest equipment models.

Moreover, the method presented here could be easily extended to other construction stages and activities, through the characterization of their related consumption agents and an analysis of corresponding load factors. For other significant earthworks types, such as civil construction, a future in-depth analysis considering different consumption agents and materials would be required to fit the predictive method.

Future research in the area of construction equipment could lead to significant benefits for both the construction industry and the environment.

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