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Sustainable earthworks: Optimization with the ICOM method

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Abstract

In the construction of highways and roads, one of the main activities is earthworks. This activity has an economic and environmental impact that cannot be overlooked. The classic method, based on the use of mass diagram models and optimization, does not take into account the type and quality of the material found on site, making it difficult to optimize the actual flow of each material. The ICOM method (Intelligent Method of Optimized Mass Compensation) allows the optimization of classic works such as excavations and fillings resulting in the optimization of operating costs. This versatile method contemplates different options for each project and allows choosing the most appropriate one taking into account, among other factors, the distance travelled by each type of material, which translates into the amount of CO_2 emitted and waste generated. This is why the use of the iCom method will enable us to make the work sustainable, while reducing environmental pollution and the amount of waste. This article compares the results obtained by applying the ICOM method with those that can be obtained with the classic method for twenty-four work projects in Spain and Portugal. The results analysed show that the ICOM method achieves a significant reduction in financial costs between 5% and 14.1% and a shortening of the time needed to carry out the work. The method also obtains a reduction in CO_2 emissions (between 5.1% and 14%), while generating a smaller volume of waste materials, which implies a reduction in environmental impact. Furthermore, this method provides the reports, plans and diagrams necessary for the complete definition of the earthworks to be carried out

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Keywords: Earth work; Optimization; Mass diagram

1. Introduction

In linear works, earth moving is a complex activity [1] that consists of the set of actions that must be carried out in the field to obtain a slope, which will be the baseline of the final path [2]. This requires the excavation and transport of large volumes of material from the areas where it is produced (cuttings and soil sources) to the places where it will be used (embankments, landfills and supply or borrow points) [3]. The cost of this task can be between 15% and 30% of the total budget of the work [4], which implies a great impact on the whole project. If

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done correctly, it can achieve an appreciable reduction in the amount of material and, consequently, a reduction in environmental impacts [5]. Classically, the linear activity planning method is based on a longitudinal balance of the materials [6] which indicates the average transport distances, but does not discriminate between types of material on the basis of their composition and quality [7], which is important because not all types of soil are suitable for any landfill [8]. This means that there could be failures in complying with construction standards that indicate the types of material that can be used for type of landfill [9–11]. This implies that the resulting compensatory soil movement may not be valid, requiring the repetition of the calculations in part, or even in full, to produce a new balancing program [12].

The volumes of materials to be excavated and transported are determined by classical methodologies (mass diagrams) [13–17] and more advanced ones, which are supported by the techniques of mathematical process optimization models [18]. Some offer the longitudinal balance of the material by indicating the average transport distances [19], and others allow efficient support for the decision-making process. However, none of them take into account the relationship between the availability of the materials and their typology.

The objective of the ICOM method is to optimize the compensatory movement of the soil. This can be defined as a series of calculations aimed at distributing and balancing the volumes of excavations and fills [20]. The fundamental principle is to transport the minimum volume of material over the shortest possible distance.

Therefore, the two parameters that determine the optimization of earthworks are volume and distance. The first refers to the amount of material that needs to be brought in or removed, starting from the initial terrain, with respect to the slope to obtain the projected platform. The second refers to the distance that this material must be transported to reach the point where it will finally be used. The combination of these two parameters gives results that determine CO_2 emissions [21], waste generation [22], time to completion [23] and related costs [24]. The ICOM method [25,26], takes into account the type of material involved, achieving greater efficiency for the process by allowing the systematization of these tasks, avoiding possible human erroneous decision.

Therefore, in practice, optimization will depend on the experience of earthmoving project manager. Earthmoving is the only area of linear work that lacks a perfectly defined plan in advance. Road structures and surfaces are completely predetermined and there is little room for manoeuvre in constructing them. In this sense, some different models have been formulated, based on linear programming techniques [27–31], which allow a more precise optimization of earthworks.

Nandgaonkar [32] proposed the application of the specific case known as the transport problem to this type of analysis. This model minimizes the increase in distance, but requires that the cutting and filling volumes be the same. Fig. 1 shows a diagram of soil quality using Spanish standards. To simplify the figure, the discharge line has been paired with the X-axis, although the boundaries between cut and fill are not the intersections with that axis, but the appearance of a horizontal tangent. In addition, volumetric coefficients are not taken into account and costs are defined as a single invariable component. A more detailed model was proposed by Mayer and Stark [33]. It includes the application of volumetric coefficients and the establishment of areas for the extraction of supplies or the dumping of waste. Unit costs are defined by adding together three items, corresponding to excavation, transport and filling operations.

The procedure in the classical method begins with the division of the axis of the works into a finite number of sections for cutting (origins or production centres) and filling (destinations or consumption centres). Borrowing pits and waste disposal sites are implemented as another section standing at a given point on the axis. The way to establish such production and consumption points has not been studied in detail, so no single agreed criterion has been established to define them [34]. This leads to a situation where all project planners or analysts have to decide which solution is the most suitable for classifying the countervailing movements, in their opinion (Fig. 2).

A complete study has recently been carried out on the situation of inert wastes in a project at Los Alcores in the Province of Seville [35]. Naskoudakis and Petroutsatou [36] published an interesting paper that provided an exhaustive set of knowledge on optimization, maintenance, productivity, timings, robotics, automatization, innovation, operator competence and the environment. The search for cost optimization continues to be the focus of researchers around the world, such as Cheng et al. [37] in Korea. In Portugal there are authors [6,16,22] who use only two variables (cost and duration) to establish a method they have developed in Portugal.

One of the main concerns to be highlighted is the greenhouse gas emissions (GGE) from the machinery used [38]. Several authors have studied methods for reducing CO_2 emissions in specific instances of the linear works, such as Wang et al. [39], or Anthonissen et al. [40].

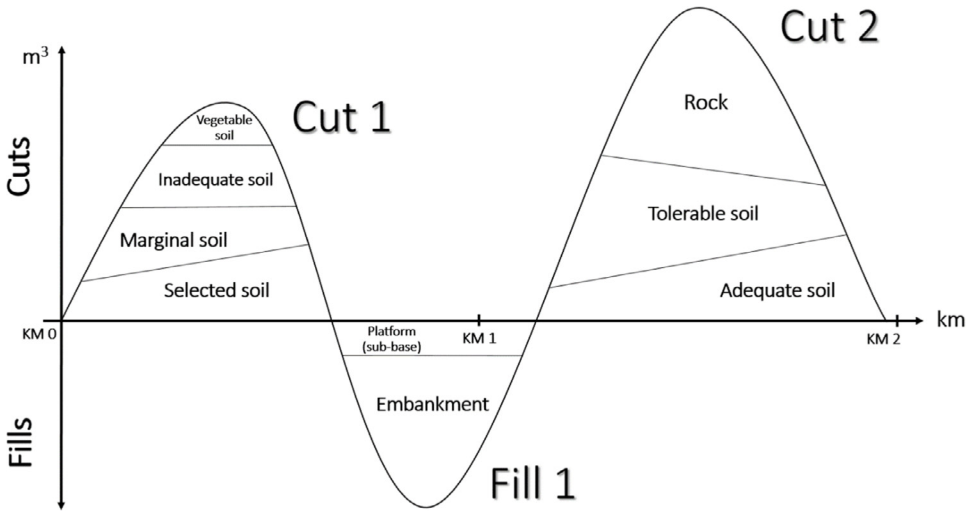

Fig. 1. Example of quality diagram.
Source: Adapted from Villar, 2018 [26].

With regard to sustainability [41], until now no comprehensive assessment covering all phases of the life cycle and the supports for it has been carried out in Europe, as there is no appropriate regulatory framework for civil organization of these issues. The appearance of LCE4ROADS [42] brought together all aspects of sustainability (environmental, financial, social and technical). The characteristics of this European certification were summarized in 2016 by the engineers of Acciona Company and made available to the academic community.

This work addresses the following challenges in the construction of linear structures:

• Quality standards: the main criterion for the classification of materials is in line with current road construction standards. These refer to the types of materials permitted for use in various types of fill, so that quality requirements are fully met.

• Volume of material and transport distances: based on the results obtained in the studied work projects, it can be concluded that the ICOM method provides a considerable reduction in the volumes of material transported and the distances over which it is transported. These are the two fundamental variables for achieving optimization in earthworks.

• Costs: as a direct result of the reduction in the volume of material and transport distances, there is also a reduction in the additional cost of transport and operating costs in relation to the classic calculation processes. This produces improvements in the financial outcomes of the project.

• Execution time: for the same reason, execution times are also reduced, with the consequent beneficial effects on the timetable for the execution of the work.

• The CO_2 emissions and the waste generated: with respect to the environment, greenhouse gas (GGE) emissions from heavy machinery are reduced. In addition, the number of supplies and material dumps is also reduced. Therefore, there is a lower volume of waste, which contributes positively to the protection of the environment.

• Simplicity in the calculation process: the ICOM method facilitates rapid adaptation to unforeseen events affecting the project. This allows the planning of earthwork to be updated providing greater versatility. In addition, the method allows the balance of the earth movement to be updated, so that any unexpected circumstances that may arise in a job of this nature can be incorporated into the calculations.

In addition to all the above, the ICOM method improves sustainability because it allows for the right decisions to be made regarding the waste generated (inadequate or marginal soils) giving the possibility of reusing the soil, as this is currently one of the greatest environmental problems. This research does not aim to say how that soil should be reused [43], but to make the decision to stabilize marginal soils on the basis of the results obtained.

The general objective of this work is to evaluate the ICOM method compared to the classical method, taking into account the three pillars of the sustainability triangle: environment, society and economy. In other words, for an earthwork to be sustainable it must be environmentally friendly, socially acceptable and economically viable. Therefore, it is proposed a global investigation of the whole process necessary for the construction of a linear work, from beginning to end. As indicated above, the ICOM method addresses the problem of mass balance, which is always present in earthworks, in a sustainable and efficient way, taking into account the environment and the type of soil available.

2. Problem description

Unlike the proposals described above (classical methods), the ICOM method makes it possible to calculate the compensatory mass movement on the basis of a classification of materials according to their type, thus ensuring that quality requirements are met [21]. It offers the possibility of discarding any of the parameters involved in the process, whether it be the type of material, obstacles, limit distance or other variables. This makes it possible to customize each earthmoving operation by taking into account all the specific characteristics and constraints that arise. It also offers the possibility of obtaining different options resulting from combinations of all these parameters as they are modified. In this way, it is possible to choose an ideal option by comparing the weighted results, whether in the form of transport distances, volume of material to be transported, completion times, waste generation, CO_2 emissions, etc. This translates to improvements in financial outcomes and greater respect for the environment.

To reach these conclusions, as noted in the introduction, the study was based on 24 projects implemented over the last 18 years. These projects involved the construction of 277 kilometres of roads and motorways, which involved the transport of more than 56 million cubic metres (m^3) of soil at a cost of more than 317 million euro.

The use of the ICOM method is an important step forward in the application of intelligent solutions, taking into account the type of material to optimize its use. Similarly, this use leads to less displacement or rejection of material and therefore is a direct step towards sustainability in this type of work or project.

The ICOM method provides a simple and accurate way to make the most of the materials found along the route line. It also minimizes the need for prior landfills or land-based sources, reducing the volume of waste generated and the emissions of harmful gases. In addition, both the distances for transporting materials and the execution time were reduced, which implied a decrease in costs and, therefore, a financial improvement in the final result of the work (Fig. 2). All of this was done in strict compliance with the quality criteria imposed by current standards.

Aggregate formulation

This section details the mathematical calculations made according to the ICOM method to optimize the mass balance. The flowchart of the ICOM method can be seen in Fig. 3.

The initial data for the ICOM method are the cut and fill volumes of each transversal profile, the typology of each soil and the characteristics of the subgrades to be executed. Different hypotheses can be made, including possible borrow pits or dumps. To understand the criteria for selecting materials in earthworks, different types of landfills and materials are identified (8): selected soils, adequate soils, tolerable soils, marginal soils and inadequate soils.

The following concepts are present in the method:

I. MOVEMENT

Movement is defined as the operation of transporting a particular type of material from an excavation to a specific fill site (see Fig. 4). It is then denoted as M_k.

II. DISTANCE BETWEEN AREAS ON A SINGLE AXIS

This is the absolute value of the difference between kilometric points (k.p.) or centres of gravity in the two areas involved in a movement (ith cut E_i and ith fill R_i). The absolute value is used because this item represents a distance between two points and therefore, by definition, it cannot have a negative value. The distance between areas will be designated as:

$$d(E_i, R_i) = \left| C_g\,(E_i) - C_g\,(R_i) \right| \quad (1)$$

where $C_g\ (E_i)$ and $C_g\ (R_i)$ stands for the centre of gravity of the ith cut and ith fill respectively.

The kilometric gravity points (k.p.) are calculated by adding the project volumes (excavations and fill sites) distributed by profiles every 20 m. In order to simplify the calculations, the centre of gravity of each area will be used instead of the volume of each profile.

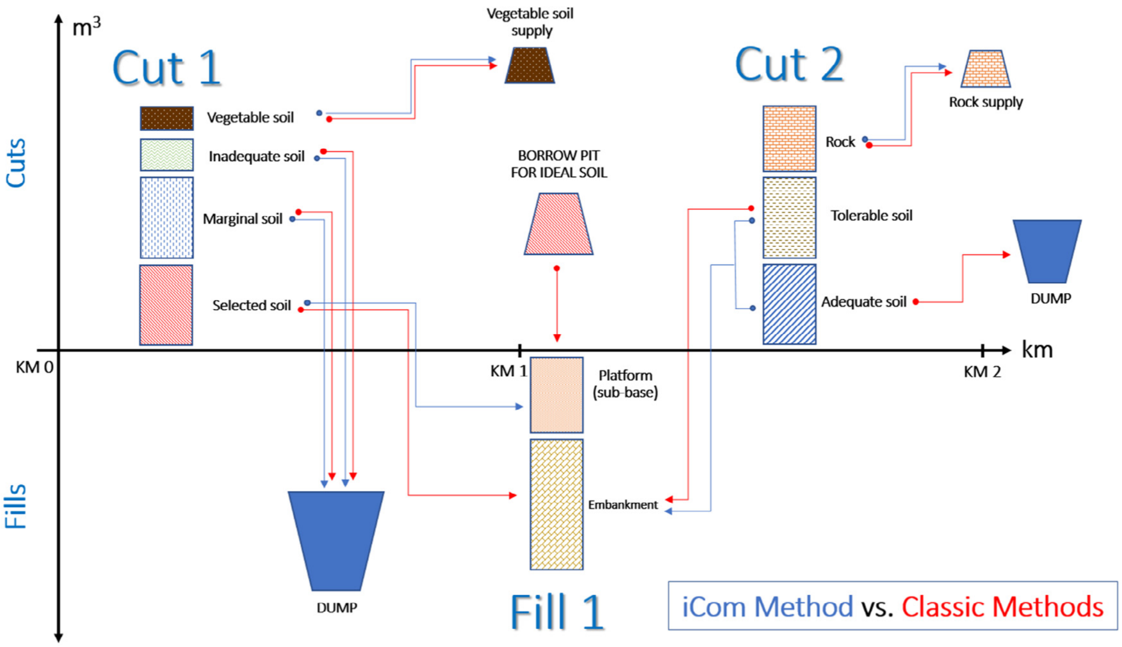

Fig. 2. Final destination of materials with the ICOM method (blue line) and classic method (red line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Source: Adapted from Villar, 2018 [26].

III. DISTANCE INCREASE

Any movement between one axis and another (as a borrow pit or a dump, an obstacle that has to be overcome or any excess distance to be travelled), will be defined as a cost of movement. When supply or dump points exist, the distance between them and the access point to the destination axis increases. From this point of entry or exit in the destination axis, the distance will be taken as the normal interval between areas on the same axis. In the case of an obstacle, this will be the additional distance that must be covered in order to get around this barrier.

The distance increase will be represented as:

$$DI = d(E_i, trunk) + d(E_i, R_i) + d(R_i, trunk) + \sum d(O_i) \tag{2}$$

where d is the distance between the elements involved and $\sum d(O_i)$ is the sum of distance increments due to the obstacles.

IV. EARTHWORKS BALANCE

The optimization of earthworks is defined as the set of calculations aimed at distributing and balancing the volumes of cut and fill, with the fundamental objective of transporting the smallest possible volume of material over the shortest possible distance. The balance is achieved by carrying out the movements corresponding to each type of soil in an orderly manner.

This means that for a certain material present in a section and for all the excavations in which this material is found, if there are one or more fillings that require this material, a soil movement will be carried out between them.

In order to define efficient, sustainable planning of earthworks for this type of work, it is necessary to establish an appropriate system of allocation of cuts and fills (see Fig. 4). Therefore, the sustainable development of these activities comprises three aspects to be considered, as defined in the Project Management Triangle: cost, scope and time. The vertex of cost represents financial issues, the vertex of scope represents environmental and technical issues as construction progresses, and the vertex of time represents issues related to the time frame for completion. In order to demonstrate the validity of the approach proposed in this document, variables related to the three project management constraints were considered:

(a) Cost, which comprises variables relating to material to be transported (m^3) and the distance over which it is transported (km). The result is the additional cost of transport (€/$m^3 \times$km).

(b) Scope, which takes into account, on the one hand, compliance with existing regulations and, on the other hand, environmental aspects including CO_2 emissions (kg CO_2/km) and reduction of waste material (m^3).

(c) Time, measured using the completion time variable (h).

The parameters calculated in the ICOM method mentioned above are presented below:

V. VOLUME OF MATERIAL TO BE TRANSPORTED

The volume of material to be transported between the ith cut and the ith fill, $V(E_i, R_i)$, is quoted in cubic metres and is the sum of all the volumes involved in all the movements that take place. This variable constitutes the basis for calculation and determines the cut-fill pairs. Any difference between the cut and fill volumes indicates the need to use borrowing pits or landfills.

VI. MOMENT OF TRANSPORT

The Moment of Transport, MT_k (in m^3 x km), is the product of the travelled distance (km) by the volume (m^3) of material corresponding to movement M_k. This variable makes it possible to compare the different earthworks balances and, to a certain extent, to optimize them: the fewer the movements, the larger their size and the shorter their distance, the more efficient the soil movement.

$$MT_k = d(E_i, R_i) \cdot V(E_i, R_i) \tag{3}$$

The moment of transport is a symbolic value that does not correspond to any physical measurement. It indicates the cost of transporting the given number of cubic metres of material $V(E_i, R_i)$ corresponding to movement M_k over the distance (in km) indicated by $d(E_i, R_i)$.

This data indicates the goodness of the balance, since it allows to know the Main Distance Transported and to compare between several possible hypotheses [25,26]. Besides this variable gives the possibility of assigning a cost per m^3 x km, so that it serves as a clear reference of what each hypothesis implies financially, as will be seen in the next section on Results. It is also a parameter of considerable utility, since it allows the deduction of costs and CO_2 emissions to be deduced, as will be seen in the following sections.

The most crucial characteristics to be taken into account are the distance transported (in km) and the volume of material transported (in m^3).

VII. MEAN DISTANCE TRANSPORTED

The Mean Distance Transported (MDT) is the absolute value of the intervals between kilometric balance points or centres of gravity in two areas involved in a movement M_k. For comparisons with the results obtained by another method, the average distance at which the material is transported, or Mean Distance Transported (in km), will be employed

$$MDT = \frac{\sum_k MT_k}{\sum_i V(E_i, R_i)} \tag{4}$$

This variable can be defined as the distance between centres of gravity of the volume in its original position and once placed in a fill site [44]. It is a significant variable because it allows comparisons with the results of the classical method, or even contrasts between several different hypotheses within the ICOM method.

VIII. SUPPLEMENTARY COST OF TRANSPORT

The Supplementary Cost of Transport C_t allows to economically comparing each one of the different alternatives considered, using the Moment *MT* and assigning a cost c (depending of the type of vehicle) to each m^3 of material transported for each metre of distance travelled

$$C_t = c \cdot MT_k \tag{5}$$

A distinction must be made between two types of transport vehicles that can be involved in earthworks: road and off-road vehicles, depending on whether or not they can be driven on public roads. For the calculation of costs, the data usually used by construction companies and public administration to evaluate transport supplements will be used by default.

Logically, these data can be modified according to the particular conditions and characteristics of each type of vehicle used. It should be noted that this is not an attempt to study costs in depth, but rather a tool that allows for the development of two or more alternatives so that they can be compared and the best option chosen.

IX. COMPLETION TIME

The Completion Time (*CT*) attempts to quantify the duration of the transport of the material. It is based on two types of data, the volume of material to be transported $V(E_i,R_i)$ and the performance foreseen per time unit P in m^3/h.

$$CT = \frac{V(E_i, R_i)}{P} \tag{6}$$

Performance will depend on the number and type of pieces of load-moving equipment available, and also of ground conditions [45]. It allows extrapolation of Operational Costs over the time that the works last, and thus a comparison of quantitative data of all the possible alternatives.

X. OPERATIONAL COSTS

Operational costs, also known as OPEX, or Operating Expenses, are a permanent cost for the operation of a product, business or system. In this study, operating expenses (OPEX) will be understood as the disbursements generated by all the elements involved in earthworks. These include the purchase or rental of machinery, together with maintenance, consumables, breakdowns, fuel, insurance, licences and payment to operators.

Due to the large number of variables involved to obtain the Operational Costs, the hourly cost is used. This includes the sum of all the costs, described above, per hour of work of each of the machines involved in the operation. Thus, the operating expenses were determined as the total hourly costs of each machine multiplied by the total working hours, which are already available because the completion time was known. A standard set of earthworks equipment was considered to consist of the following machines:

(a) 1 loading machine (excavator, loader or backhoe)
(b) X lorries (the number depending on the distances to be covered and the size of the lorries)
(c) 1 spreading machine (bulldozer, grader or both)
(d) 1 compactor (if needed)
(e) Others, if required (water wagon, rollers, drills)

The costs are established, in particular of the equipment used for earthworks and the time spent on it. This allows for the calculation of operating costs using the following formula:

$$C_{OPEX} = \sum C_e\, t = t \sum C_e \tag{7}$$

where C_{OPEX} is the cost of operation, $\sum C_e$ is the total cost of the equipment (per hour), and t is the realization time in hours.

As with the previous parameters, this data will be very useful for considering various possibilities of execution, choosing the one with the lowest cost, as well as offering an approximate view of the cost of the work carried out.

XI. CO_2 EMISSIONS

The calculation of the CO_2 emitted (E_{CO2}) into the atmosphere by transport vehicles can be done in several different ways. A distinction is made between three methods depending on the data available:

(a) Litres of fuel (usually diesel) consumed.
(b) Monetary value (in euro) associated with the consumption of fuel.
(c) Kilometres travelled and type of vehicle (diesel or petrol, road or off-road).

Here, option (c) will be used. Its inputs are the kilometres travelled and the type of vehicle used.

The first figure can be obtained from the total distance and quantity of material transported, using the sum of Moments of Transport Eq. (2). In addition, the volume of material that is transported by a truck on each trip must be established and a volume is specified for each type of truck available for the job. A further piece of information, the type of vehicle, gives access to the information published by official organizations on the CO_2 emissions from each type of vehicle, according to its characteristics: make, model, type of fuel and weight. The publications of the official organizations give details of the emission factors (Ef_{CO2}) expressed in kilograms of carbon dioxide per kilometre (kg CO_2/km), broken down by category and type of driving [46].

Thus, given the kilometres travelled and by extracting the emission data from the vehicles used for transporting material, the CO_2 emissions (in kg) are calculated by the formula:

$$E_{CO_2} = \sum_i d(E_i, R_i) \times Ef_{CO_2} \tag{8}$$

As with the additional cost of transport, this document does not attempt to provide a comprehensive calculation of CO_2 emissions from vehicles. Rather, it seeks to obtain an objective figure that will allow for the estimation and comparison of the various alternatives so that the least environmentally damaging one can be chosen.

XII. WASTE GENERATED

Waste generated (Wg) is understood to be surplus materials that must be deposited in dumps. Inert waste is described in Spanish Royal Decree 1481/2001 as waste that does not undergo significant physical, chemical or biological transformations. Such materials are not soluble and run no risk of catching fire. They do not react physically or chemically and are not biodegradable. They do not affect materials with which they come into contact, release very few leachates, and are of low toxicity. They pose no risk to surface or underground water. The reference is to soil and aggregates.

Although the material may be useful for other purposes, there are three reasons why this type of waste may be generated:

(a) There is a surplus material because the amount coming from the cuts is greater than that required in the fillings.

(b) Excavated material is not of the quality required for use in fills at that stage.

(c) The soil balance is not well calculated and materials of a higher quality than required for the fills are used which have more tolerance with respect to quality conditions. The result is that when fills have to be carried out with stricter quality requirements, no appropriate material remains. This is one of the main disadvantages of the classical method solved by the ICOM method.

The waste generated Wg (in m^3) would be equal to the material transported to the dumps. This is calculated by deducting the volume of material used in all the fills from the amount excavated, following the formula:

$$Wg = \sum_i V(E_i) - \sum_i V(R_i) \tag{9}$$

Fig. 3 shows the block diagram used to represent the whole process performed under the ICOM method to calculate the optimized balance of masses in linear works [25].

Considering a space of a linear work as an axis, a section is a cross section of any axis. An area is a part of an axis, which must be an excavation or a fill. Therefore, a subarea is a type of fill or excavation within the area. Finally, an obstacle is any element that can interrupt transport, such as a bridge, tunnel, viaduct, etc. Fig. 3 details the three phases of the ICOM method: Phase 1. Project data collection, Phase 2. Calculation of the moment of transport, which is the data that allows knowing the optimization of the project, and Phase 3: Obtaining the values of the parameters involved in the ICOM method.

In the characterization of the material, the criterion used was the specification in the general technical requirements brochure for roads and bridges published by the Spanish General Directorate of Roads (PG-3).

In addition to the five types of soil described by the standard (Table 1), two other types must be distinguished, rock and vegetable soil. Due to their special characteristics relative to excavation or use, these should be considered separately.

It is possible to relate the Spanish standard in Table 1 with AASHTO (American Association of State Highway and Transportation Officials) (9) standard, as follows: Selected soil (A1), Adequate soil (A2), Tolerable soil (A3), Marginal soil (A4–A5) and Inadequate soil (A6–A7).

In linear works, rock is understood as the material whose hardness makes excavation impossible with normal mechanical equipment. This makes it necessary to use blasting or lateral displacement. Once removed, this material is generally much thicker than those listed in the above classification. For this reason, it is placed in a separate grouping.

Furthermore, vegetable soil (or soil with organic matter content of more than 5%) would fall into the Inadequate Soil group. However, due to its usefulness for re-instating and replanting embankments, dumps, quarries and similar, it is preferable to consider it separately (Fig. 4). Once the materials existing in the cuttings have been characterized and the different types of fill, embankment and subgrade, have been defined, a balance can be made of the land in which the movements are optimal, in terms of both transport distances and execution times, in strict compliance with the quality criteria required in current regulations.

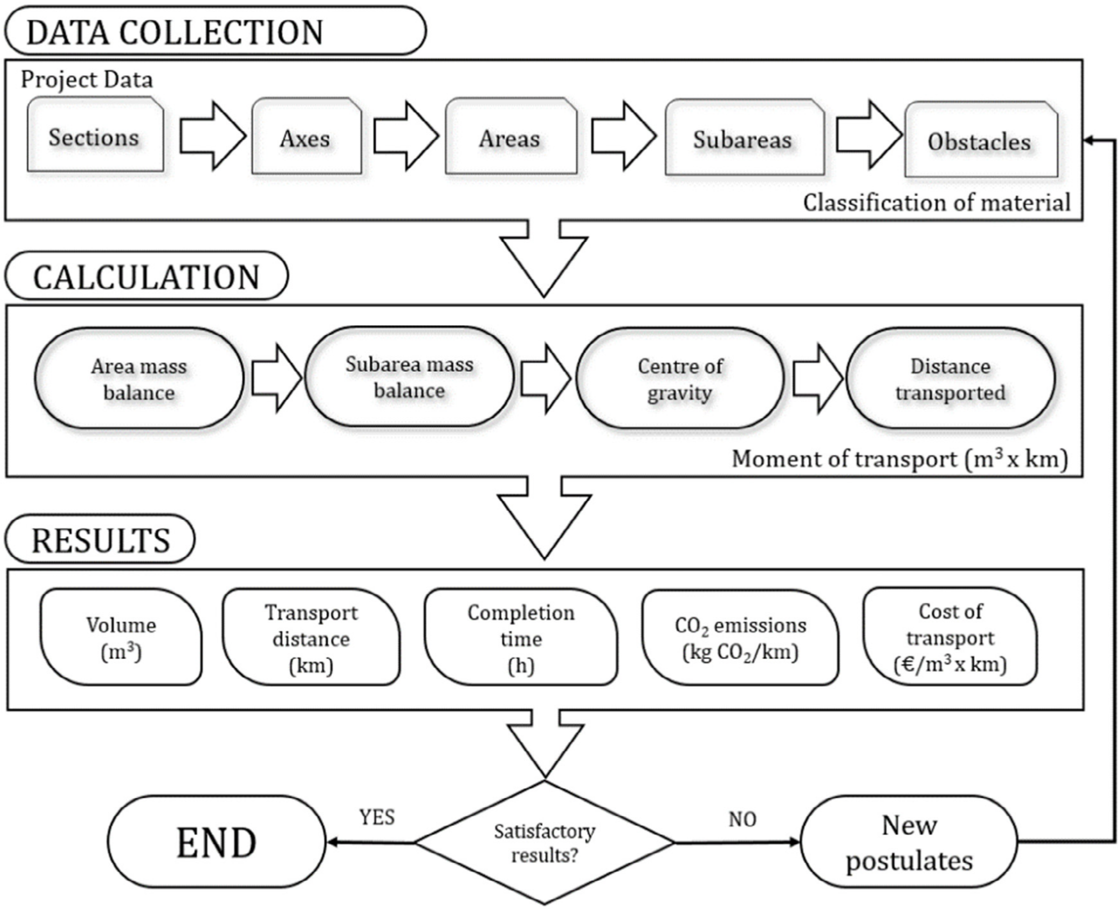

Fig. 3. ICOM method calculation phases.
Source: Adapted from Villar, 2018 [26].

Table 1. Types of material considered in accordance with applicable standard (PG-3).

Terms	Selected S.	Adequate S.	Tolerable S.	Marginal S.	Inadequate S.
Content in organic matter	< 0.2%	< 1%	< 2%	< 5%	> 5%
Content in soluble salts in water	< 0.2%	< 0.2%	< 1%	< 1%	> 1%
Maximum size	≤ 100 mm	≤ 100 mm	–	—	–
Sifting through the 2 UNE sieve	< 80%	< 80%	–	—	–
Sifting through the 0.40 UNE sieve	< 15%	–	—	–	–
Sifting through the 0.080 UNE sieve	< 25%	< 35%	–	—	–
Liquid limit according to UNE 103 103	< 30	< 40	< 65	< 90	> 90
Plasticity index according to UNE 103103–4	< 10	> 4	> 0.73	< 0.73	> 0.73
Seat in collapse test according to NLT-254	–	—	< 1%	–	–
Free swelling according to UNE 103 601	–	—	< 3%	< 5%	> 5%

3. Results and discussion

The data corresponding to the sum of the transport moments, provided by the ICOM method, reflects the degree of optimization of the process. Thus, the lower this quantity is, the greater the degree of optimization obtained.

As noted above, this article compares the ICOM method with the classical method in twenty-four construction projects where earthmoving represented a significant part of the overall project, between 15% and 30% of the overall budget. In order to demonstrate the validity and effectiveness of the procedure designed, the optimization

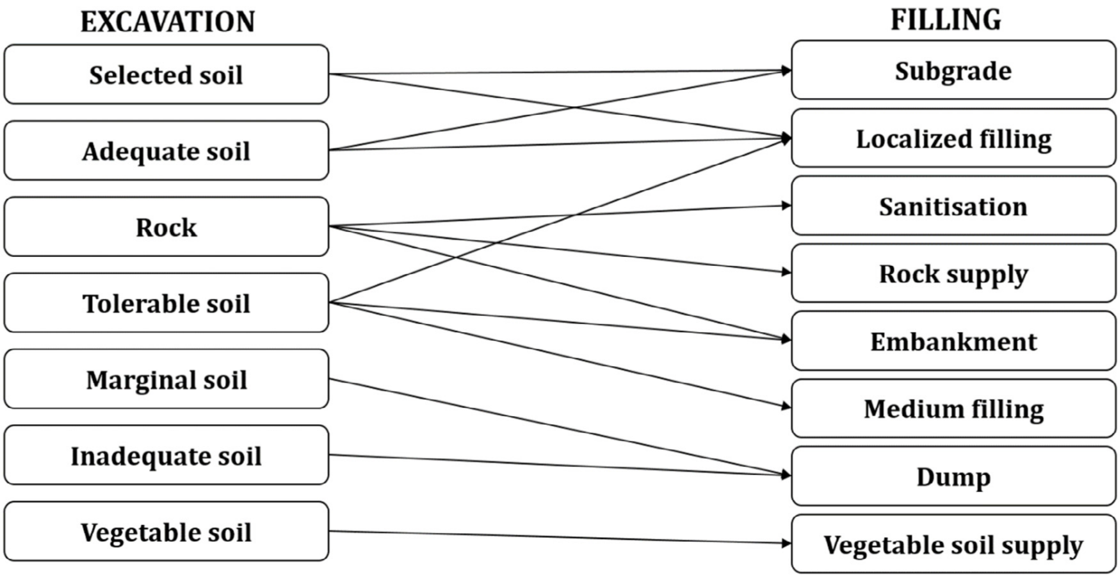

Fig. 4. Priorities for balance of cutting and fill materials.
Source: Adapted from Villar, 2018 [26].

of earthmoving on the twenty-four sites was calculated first using the classical method and then the ICOM method. The values of expenditure, time and emissions were also determined as indicated in the previous section.

Table 2 shows the values of completion date, distance travelled by the different materials and their volume for the twenty-four projects studied. These data are completed by the type of work, its name and associated sections, and the country where it was carried out.

Among all the projects mentioned, one is chosen as a practical example of the comparison between the classical method and the ICOM method. This comparison makes it possible to easily analyse the results and to quantify the reduction or savings obtained in each of the factors described above. In this case project 23 has been chosen, corresponding to Section 2 of the A66 Benavente-Zamora motorway (Spain). The total length of this section is 17.7 km, with a cutting volume of 1 167 305 m^3 and 1 131 993 m^3 of landfill. The following materials were used for the excavation work:

- Vegetable soil: 20 595 m^3
- Tolerable soil: 451 420 m^3
- Adequate soil: 540 931 m^3
- Selected soil:154 359 m^3

The volume of material to be transported is distributed over the following fillings:

- Embankment: 772 495 m^3
- Localized filling: 211 107 m^3
- Subgrade: 127 796 m^3
- Vegetable soil supply: 20 595 m^3

Based on the initial data, the earth compensation and the movements of each type of material are calculated with each method. These results are shown in Table 3.

Table 4 shows a summary of the results obtained for Project 23 with the classical method and the ICOM method. Each of the variables involved and the type of material have been taken into account, according to the points described in the previous section (from I to XII). The first two columns of the table show, for both methods, the values corresponding to the different parameters. The third and fourth columns contain the difference of the mentioned values, and a percentage of savings that could be described as optimization.

Table 2. List of work projects constituting the basis of the study.

Nº	Country	Type	Name of project	Completion date	Distance (km)	Volume (m^3)
1	Portugal	Motorway	IC-4 – Alcantarilha / Lagos	01/02/2002	25	1,590,000
2	Portugal	Motorway	IC-4 – Alcantarilha / Lagos	01/04/2002	13	1,780,000
3	Portugal	Motorway	IC-4 – Alcantarilha / Lagos	01/05/2002	15	1,550,000
4	Portugal	Toll Motorway	A11-IP9 - Braga and Guimarães	01/08/2002	17	2,300,000
5	Portugal	By-Pass	Alternative route to EN 14 - Braga by-pass	01/08/2002	15	710,000
6	Portugal	Football Stadium	Access to New Stadium in Braga	01/10/2002		500,000
7	Portugal	Football Stadium	Access to New Stadium in As Antas	01/03/2003		1,570,000
8	Portugal	Railway	Double-tracking and electrification, Minho line	02/05/2003	10	950,000
9	Portugal	Highway	Alternative route to EN 326	01/08/2003	9	1,100,000
10	Portugal	Toll Motorway	A7/IC5/IC25	01/12/2003	9	2,600,000
11	Portugal	Toll Motorway	A7/IC5/IC25	01/05/2004	19	6,500,000
12	Portugal	Toll Motorway	A7/IC5/IC25	01/05/2004	15	4,750,000
13	Portugal	Toll Motorway	"Grande Porto" Motorway/IC24/IC25	01/11/2004	9	2,750,000
14	Portugal	Highway	Alternative route to EN321–1	01/04/2005	8	750,000
15	Portugal	Toll Motorway	"Interior Norte" Motorway/IP3	01/06/2005	9	3,500,000
16	Portugal	Toll Motorway	A7/IC5/IC25	01/09/2005	9	3,100,000
17	Portugal	Toll Motorway	A11-IP9	01/11/2005	9	3,100,000
18	Portugal	Toll Motorway	A11-IP9	01/12/2005	6	2,400,000
19	Portugal	Toll Motorway	A11-IP9	01/01/2006	8	2,700,000
20	Spain	Motorway	Motorway A – 67: Alar del Rey-Nogales P.	01/11/2009	6	2,000,000
21	Spain	Motorway	Motorway A 60: Valladolid - León	01/08/2012	17	3,120,000
22	Spain	Motorway	Motorway A66: Benavente - Zamora	01/09/2015	15	2,400,000
23	Spain	Motorway	Motorway A66: Benavente - Zamora	01/09/2015	17	1,300,000
24	Spain	Motorway	Motorway A66: Benavente - Zamora	01/09/2015	17	2,300,000
					277	**55,320,000**

Table 3. Example Project 23: Comparison between ICOM method and Classic method.

ORIGIN	DESTINATION	MATERIAL	Volume (m^3)		
			Classic method	ICOM method	Difference
CUT	SUPPLY	VEGETABLE SOIL	20,595	20,595	0
CUT	DUMP	TOLERABLE SOIL	163,108	35,312	−127,796
CUT	EMBANKMENT	TOLERABLE SOIL	288,312	416,108	127,796
CUT	EMBANKMENT	ADEQUATE SOIL	329,824	356,387	26,563
CUT	LOCALIZED FILLING	ADEQUATE SOIL	211,107	184,544	
CUT	EMBANKMENT	SELECTED SOIL	154,359		
CUT	LOCALIZED FILLING	SELECTED SOIL		26,563	26,563
CUT	ESPLANADE	SELECTED SOIL		127,796	127,796
BORROW PIT	ESPLANADE	SELECTED SOIL	127,796		−127,796
		TOTAL	**1,295,101**	**1,167,305**	**−127, 796**

This has been an example of how the percentage reduction of each of the factors determined by the ICOM method (CO_2 emissions, volume of waste, additional transport and operating costs, time of completion, etc.) is calculated. Tables 5.1 and 5.2 show a summary of the results obtained for the 24 works mentioned in Table 2. The columns in the tables contain the results of the following factors:

- Moment of Transport (m^3 x km)
- Total Volume Transported (m^3)
- Sup. Transport Cost (€)
- Completion Time (h)
- Operating Costs OPEX (€)
- CO_2 Emissions (kg CO_2/km)
- Waste (m^3)

Table 4. Resume results for Project 23 of Table 2.

Concept	Units	Classical method	ICOM method	Difference	Savings (%)
I - IV - TOTAL DISTANCE TRANSPORTED	km	20,889	18,340	2,549	12.2%
V - VOLUME TRANSPORTED	m^3	1,295,101	1,167,305	127,796	9.9%
VI - MOMENT OF TRANSPORT					
Sum of Moment of transport	m^3 x km	626,666	550,189	76,476	12.2%
VII - MAIN DISTANCE TRANSPORTED					
Main distance transported (km)	km	0.484	0.471	0.013	
Main distance transported - Off-road* (km)	km	21	18	3	12.2%
Main distance transported - road* (km)	km	52	46	6	12.2%
* Off-road = 30 m^3/load. Road = 12 m^3/load					
VIII - SUPPLEMENTARY COST OF TRANSPORT					
Off-road vehicles (0.24 €/m^3x km)	€/m^3 x km	150	132	18	12.2%
Road vehicles (0.26 €/m^3x km)	€/m^3 x km	163	143	20	12.2%
IX - COMPLETION TIME					
Equipment Performance (h)*	h	4,317	3,891	426	9.9%
* We assume for the example a performance per team of 300 m^3/h					
X - OPERATIONAL COSTS (OPEX)					
Cost earthworks equipment (750 €/h)*	€	3,237,753	2,918,264	319 489	9.9%
* We assume for the example a cost per team of 750 €/h					
XI - CO_2 EMISSIONS					
Off-road vehicles (0.947 kg CO_2/km)*	kg CO_2/km	20	17	2	12.2%
Road vehicles (0.646 kg CO_2/km)*	kg CO_2/km	34	30	4	12.2%
* We assume for example the CO_2 emissions published					
XII - WASTE GENERATED					
Waste material	m^3	163,108	35,312	127,796	78.4%

obtained with the classical method and with the ICOM method, as well as the savings expressed as a percentage. Each of the rows corresponds to one of the 24 projects.

As can be seen, the reduction or savings for the different parameters is between 5.0% and 14.1%, except in the case of waste, which depends on other criteria, as seen in Section 2, point IX.

4. Conclusions

In this article, earthworks corresponding to 24 linear works carried out in the Iberian Peninsula have been studied. Earthworks have been calculated taking into account the ICOM method, which optimizes the flow of materials that takes place during the project.

This optimization is due to the fact that each material is used for a specific job (filling, recycling of supplies and waste) within the project, which makes it possible to foresee the quantity and type of material to be transported, as well as the duration of the journey.

As a main advantage, the ICOM method uses the information available at each stage of the project by managing earthworks in an optimal way. The method can be applied at all stages of the project. At the design stage, the method ensures the best choice of balance with the geological, topographical or other materials data available. In the planning stage it chooses the best hypothesis among all those calculated and in the execution stage, with the most reliable information available about the materials, being much more precise imagining all the plausible hypotheses, and selecting the most appropriate one. In the evaluation and monitoring stage it allows the monitoring of the work, having the data updated at all times, and in the presentation of results with all the information of the work actually executed, obtaining reports, movement lists, mass diagram, etc.

Table 5.1. Summary of results for the first twelve work projects studied.

Project no.	Method used	Moment of transport (m^3 x km)	Total volume transported (m^3)	Sup. transport cost (€)		Completion time (h)	Operating costs OPEX (€)	CO_2 emissions (kg CO_2/km)		Waste (m^3)
				Off-road	On-road			Off-road	On-road	
	Classic	7 232 882	1 590 357	1,735,892	1,880,549	5,301	3,975,893	228,318	389,370	269,873
1	ICOM	6 331 817	1 411 777	1,519,636	1,646,272	4,706	3,529,443	199,874	340,863	239,584
	Savings	**901 065**	**178 580**	**12.5%**	**12.5%**	**11.2%**	**11.2%**	**12.5%**	**12.5%**	**11.2%**
	Classic	3 698 243	1 779 040	887,578	961,543	5,930	4,447,600	116,741	199,089	357,449
2	ICOM	3 497 170	1 636 754	839,321	909,264	5,456	4,091,885	110,394	188,264	215,163
	Savings	**201 073**	**142 286**	**5.4%**	**5.4%**	**8.0%**	**8.0%**	**5.4%**	**5.4%**	**39.8%**
	Classic	6 983 215	1 551 672	1,675,972	1,815,636	5,172	3,879,180	220,437	375,930	342,112
3	ICOM	6 354 726	1 326 071	1,525,134	1,652,229	4,420	3,315,178	200,598	342,096	57,786
	Savings	**628 489**	**225 601**	**9.0%**	**9.0%**	**14.5%**	**14.5%**	**9.0%**	**9.0%**	**83.1%**
	Classic	7 422 051	2 288 929	1,781,292	1,929,733	7,630	5,722,323	234,289	399,554	73,658
4	ICOM	6 776 332	2 051 850	1,626,320	1,761,846	6,840	5,129,625	213,906	364,793	73,658
	Savings	**645 718**	**237 079**	**8.7%**	**8.7%**	**10.4%**	**10.4%**	**8.7%**	**8.7%**	**0.0%**
	Classic	815 329	709 505	195,679	211,985	2,365	1,773,763	25,737	43,892	134,404
5	ICOM	716 066	636 421	171,856	186,177	2,121	1,591,053	22,604	38,548	97,862
	Savings	**99 263**	**73 084**	**12.2%**	**12.2%**	**10.3%**	**10.3%**	**12.2%**	**12.2%**	**27.2%**
	Classic	450 633	502 500	108,152	211,985	1,675	1,256,250	14,225	24,259	500,000
6	ICOM	427 605	477 500	102,625	111,177	1,592	1,193,750	13,498	23,019	475,000
	Savings	**23 027**	**25 000**	**5.1%**	**47.6%**	**5.0%**	**5.0%**	**5.1%**	**5.1%**	**5.0%**
	Classic	9 587 430	1 570 000	2,300,983	2,492,732	5,233	3,925,000	302,643	516,123	850,000
7	ICOM	9 068 502	1 490 000	2,176,441	2,357,811	4,967	3,725,000	286,262	488,188	800,000
	Savings	**518 928**	**80 000**	**5.4%**	**5.4%**	**5.1%**	**5.1%**	**5.4%**	**5.4%**	**5.9%**
	Classic	2 586 987	955 025	620,877	672,617	3,183	2,387,563	81,663	139,266	31,739
8	ICOM	2 370 508	891 547	568,922	616,332	2,972	2,228,868	74,829	127,612	0
	Savings	**216 479**	**63 478**	**8.4%**	**8.4%**	**6.6%**	**6.6%**	**8.4%**	**8.4%**	**100.0%**
	Classic	1 458 633	1 100 062	350,072	379,245	3,667	2,750,155	46,044	78,523	86,452
9	ICOM	1 327 173	1 023 610	318,521	345,065	3,412	2,559,025	41,894	71,446	10,000
	Savings	131 460	76 452	9.0%	9.0%	6.9%	6.9%	9.0%	9.0%	88.4%
	Classic	7 421 986	2 632 000	1,781,277	1,929,716	8,773	6,580,000	234,287	399,550	793,000
10	ICOM	6 668 926	2 452 000	1,600,542	1,733,921	8,173	6,130,000	210,516	359,011	613,000
	Savings	753 060	180 000	10.1%	10.1%	6.8%	6.8%	10.1%	10.1%	22.7%
	Classic	9 715 105	6 577 626	2,331,625	2,525,927	21,925	16,444,065	306,673	522,996	1,556,146
11	ICOM	8 709 883	6 100 450	2,090,372	2,264,570	20,335	15,251,125	274,942	468,882	313,879
	Savings	**1 005 222**	**477 176**	**10.3%**	**10.3%**	**7.3%**	**7.3%**	**10.3%**	**10.3%**	**79.8%**
	Classic	9 782 365	4 747 812	2,347,768	2,543,415	15,826	11,869,530	308,797	526,617	797,161
12	ICOM	8 412 834	4 486 851	2,019,080	2,187,337	14,956	11,217,128	265,565	452,891	536,200
	Savings	**1 369 531**	**260 961**	**14.0%**	**14.0%**	**5.5%**	**5.5%**	**14.0%**	**14.0%**	**32.7%**

Table 5.2. Summary of results for the following twelve work projects studied.

Project no.	Method used	Moment of transport (m^3 x km)	Total volume transported (m^3)	Sup. transport cost (€)		Completion time (h)	Operating costs OPEX (€)	CO_2 emissions (kg CO_2/km)		Waste (m^3)
				Off-road	On-road			Off-road	On-road	
	Classic	4 256 921	2 752 326	1,021,661	1,106,800	9,174	6,880,815	134,377	229,164	528,648
13	ICOM	3 731 399	2 458 746	895,536	970,164	8,196	6,146,865	117,788	200,874	235,068
	Savings	**525 522**	**293 580**	**12.3%**	**12.3%**	**10.7%**	**10.7%**	**12.3%**	**12.3%**	**55.5%**
	Classic	985 675	763 788	236,562	256,275	2,546	1,909,470	31,114	53,062	215,192
14	ICOM	899 513	711 240	215,883	233,873	2,371	1,778,100	28,395	48,424	201,734
	Savings	**86 161**	**52 548**	**8.7%**	**8.7%**	**6.9%**	**6.9%**	**8.7%**	**8.7%**	**6.3%**
	Classic	5 578 710	3 457 030	1,338,890	1,450,465	11,523	8,642,575	176,101	300,321	746,000
15	ICOM	4 909 264	3 187 030	1,178,223	1,276,409	10,623	7,967,575	154,969	264,282	476,000
	Savings	**669 445**	**270 000**	**12.0%**	**12.0%**	**7 8%**	**7.8%**	**12.0%**	**12.0%**	**36.2%**
	Classic	4 389 726	3 132 583	1,053,534	1,141,329	10,442	7,831,458	138,569	236,314	1,531,078
16	ICOM	4 142 382	2 974 257	994,172	1,077,019	9,914	7,435,643	130,761	222,998	1,372,752
	Savings	**247 343**	**158 26**	**5.6%**	**5.66%**	**5.1%**	**5.1%**	**5.6%**	**5.6%**	**10.3%**
	Classic	6 498 753	3 102 042	1,559,701	1,689,676	10,340	7,755,105	205,144	349,850	0
17	ICOM	6 108 828	2 830 390	1,466,119	1,588,295	9,435	7,075,975	192,835	328,859	0
	Savings	**389 925**	**271 652**	**6.0%**	**6.0%**	**8.8%**	**8.8%**	**6.0%**	**6.0%**	**0.0%**
	Classic	8 953 219	2 409 741	2,148,773	2,327,837	8,032	6,024,353	282,623	481,982	197,312
18	ICOM	7 690 188	2 079 351	1,845,645	1,999,449	6,931	5,198,378	242,754	413,988	0
	Savings	**1 263 031**	**330 390**	**14.1%**	**14.1%**	**13.7%**	**13.7%**	**14.1%**	**14.1%**	**100.0%**
	Classic	9 814 867	2 709 286	2,355,568	2,551,865	9,031	6,773,216	309,823	528,367	713,681
19	ICOM	9 127 826	2 572 389	2,190,678	2,373,235	8,575	6,430,973	288,135	491,381	673,681
	Savings	**687 041**	**136 897**	**7.0%**	**7.0%**	**5.1%**	**5.1%**	**7.0%**	**7.0%**	**5.6%**
	Classic	306 055	2 012 404	73,453	79,574	6,708	5,031,010	9,661	16,476	97,722
20	ICOM	266 135	1,903,652	63,872	69,195	6,346	4,759,130	8,401	14,327	43,346
	Savings	**39 920**	**108 752**	**13.0%**	**13.0%**	**5.4%**	**5.4%**	**13.0%**	**13.0%**	**55.6%**
	Classic	2 236 916	3 121 271	536,860	581,598	10,404	7,803,178	70,612	120,421	1,004,981
21	ICOM	2 089 015	2 957 021	501,364	543,144	9,857	7,392,553	65,943	112,459	952,856
	Savings	**147 901**	**164 250**	**6.6%**	**6.6%**	**5.3%**	**5.3%**	**6.6%**	**6.6%**	**5.2%**
	Classic	1 189 161	2 457 583	285,399	309,182	8,192	6,143,958	37,538	64,016	46,652
22	ICOM	1 055 699	2 307 043	253,368	274,482	7,690	5,767,608	33,325	56,832	46,652
	Savings	**133 462**	**150 540**	**11.2%**	**11.2%**	**6.1%**	**6.1%**	**11.2%**	**11.2%**	**0.0%**
	Classic	626 666	1 295 101	150,400	162,933	4,317	3,237,753	19,782	33,736	163,108
23	ICOM	550 189	1 167 305	132,045	143,049	3,891	2,918,264	17,368	29,619	35,312
	Savings	**76 476**	**127 796**	**12.2%**	**12.2%**	**9.9%**	**9.9%**	**12.2%**	**12.2%**	**78.4%**
	Classic	8 914 867	2 320 568	2,139,568	2,317,865	7,735	5,801,420	281,413	479,917	362,556
24	ICOM	8 005 042	2 172 324	1,921,210	2,081,311	7,241	5,430,811	252,692	430,938	124,096
	Savings	**909 825**	**148 244**	**10.2%**	**10.2%**	**6.4%**	**6.4%**	**10.2%**	**10.2%**	**65.8%**

This translates into savings, not only in the budget, but also in CO2 emissions and in the days of the complete work, avoiding unnecessary inconvenience to users.

The ICOM method is capable of making an a priori estimate, quickly and free of charge, of the CO_2 generated, choosing the optimal hypothesis with fewer emissions and waste, which is economically profitable. It can also, once the optimal earthmoving option has been chosen, give an approximate figure of the reduction in the cost of the work, compared to other options, and the consequent energy savings linked to the lower CO_2 emissions.

It should be noted that the ICOM method could be applied to any earthmoving project taking into account all possible factors, regardless of the type of project being carried out.

In the light of the results of this public works analysis study, it can be concluded that the improvement or optimization in the movement of earth that is achieved with the ICOM method is in a range between 5.0% and 14.1%, which provides both economic and environmental benefits, reducing pollution and waste generated. Therefore, it enables construction to be made more sustainable and environmentally friendly.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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