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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 CO₂ 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 CO₂ 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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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 CO₂ 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 CO₂ emissions in specific instances of the linear works, such as Wang et al. [39], or Anthonissen et al. [40].

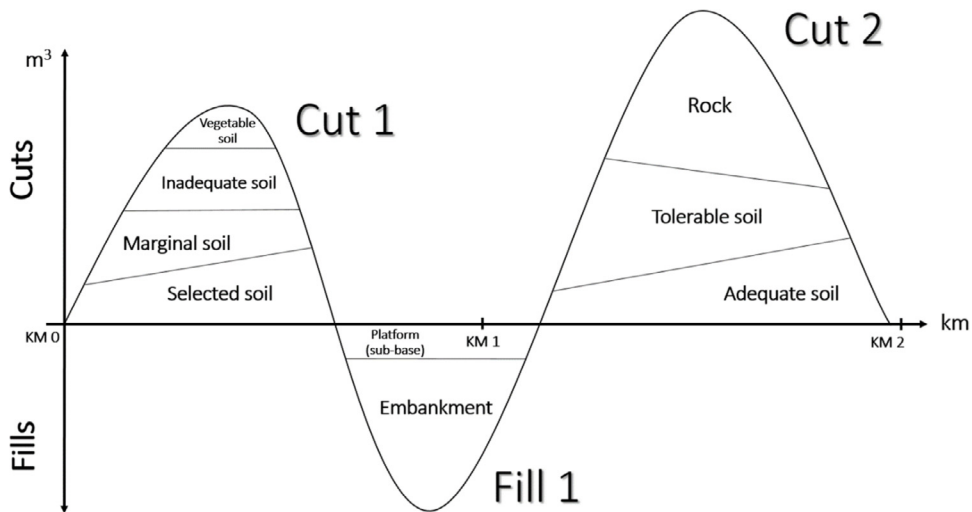


Fig. 1. Example of quality diagram.
 Source: Adapted from Villar, 2018 [26].

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 CO₂ 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, CO₂ 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 (m³) 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 (i th cut E_i and i th 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:

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

where $C_g(E_i)$ and $C_g(R_i)$ stands for the centre of gravity of the i th cut and i th 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.

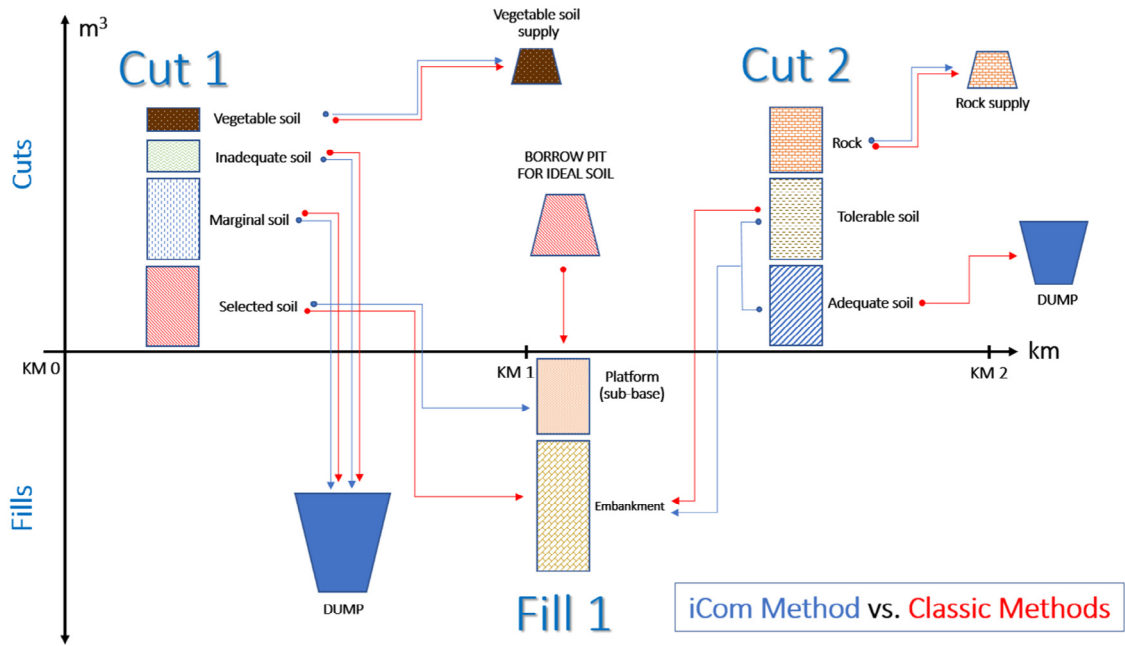


Fig. 2. Final destination of materials with the ICOM method (blue line) and classic method (red line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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:

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

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 ($\text{€}/m^3 \times \text{km}$).

(b) Scope, which takes into account, on the one hand, compliance with existing regulations and, on the other hand, environmental aspects including CO₂ emissions (kg CO₂/km) and reduction of waste material (m³).

(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 i th cut and the i th 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 m³ x km), is the product of the travelled distance (km) by the volume (m³) 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.

$$MT_k = d(E_i, R_i) \cdot V(E_i, R_i) \quad (3)$$

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 m³ 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 CO₂ 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 m³).

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

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

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 m³ of material transported for each metre of distance travelled

$$C_t = c \cdot MT_k \quad (5)$$

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 .

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

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:

$$C_{OPEX} = \sum C_e t = t \sum C_e \quad (7)$$

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. CO₂ EMISSIONS

The calculation of the CO₂ emitted (E_{CO_2}) 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 CO₂ 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_{CO_2}) expressed in kilograms of carbon dioxide per kilometre (kg CO₂/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 CO₂ emissions (in kg) are calculated by the formula:

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

As with the additional cost of transport, this document does not attempt to provide a comprehensive calculation of CO₂ 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 (*W_g*) 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 *W_g* (in m³) 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:

$$W_g = \sum_i V(E_i) - \sum_i V(R_i) \quad (9)$$

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.

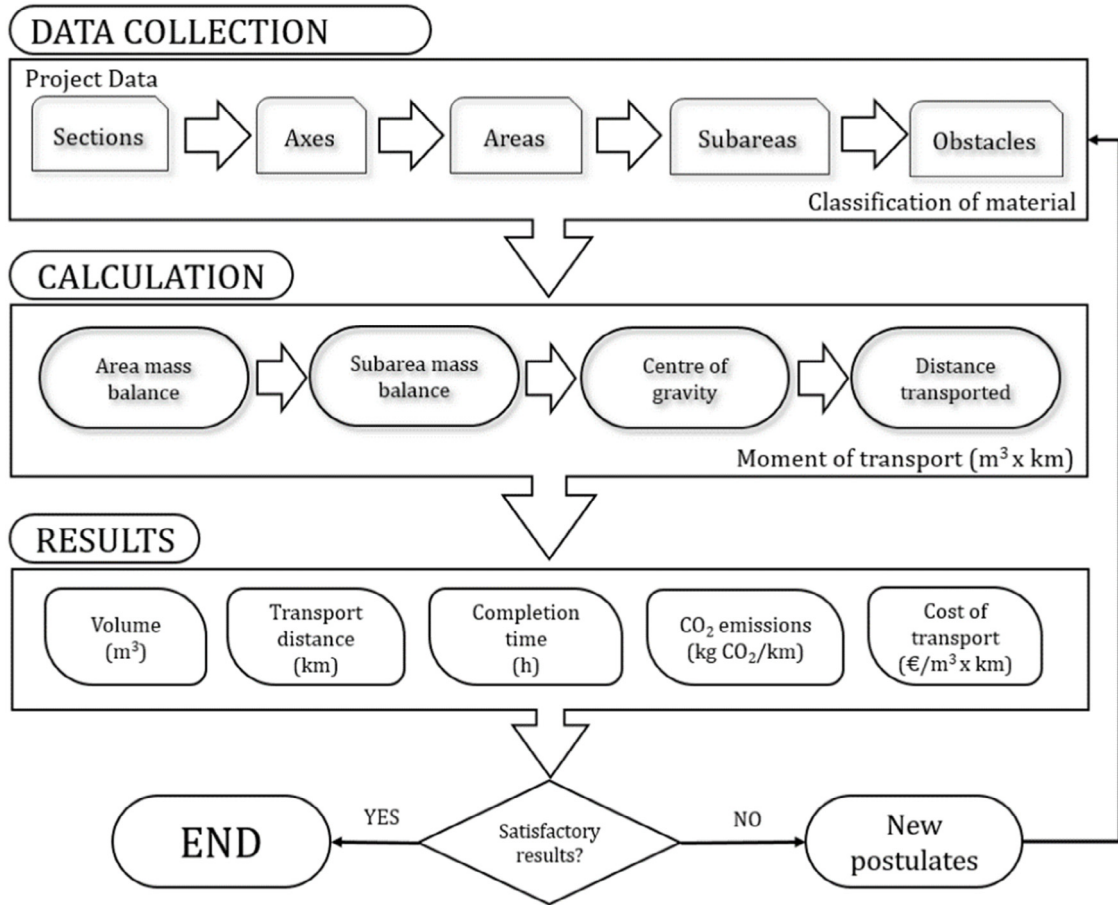


Fig. 3. ICOM method calculation phases.

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

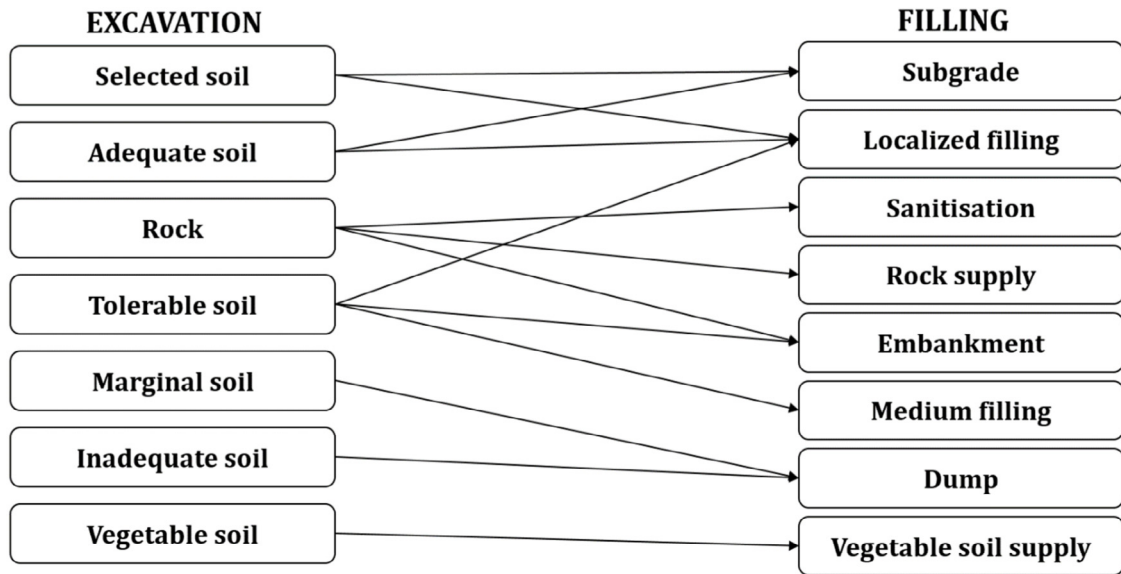


Fig. 4. Priorities for balance of cutting and fill materials.
 Source: Adapted from Villar, 2018 [26].

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 m³ and 1 131 993 m³ of landfill. The following materials were used for the excavation work:

- Vegetable soil: 20 595 m³
- Tolerable soil: 451 420 m³
- Adequate soil: 540 931 m³
- Selected soil: 154 359 m³

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

- Embankment: 772 495 m³
- Localized filling: 211 107 m³
- Subgrade: 127 796 m³
- Vegetable soil supply: 20 595 m³

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 (CO₂ 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 (m³ x km)
- Total Volume Transported (m³)
- Sup. Transport Cost (€)
- Completion Time (h)
- Operating Costs OPEX (€)
- CO₂ Emissions (kg CO₂/km)
- Waste (m³)

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 ³ x km) | €/m ³ x km | 150 | 132 | 18 | 12.2% |
| Road vehicles (0.26 €/m ³ x 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 | |
| 1 | Classic | 7 232 882 | 1 590 357 | 1,735,892 | 1,880,549 | 5,301 | 3,975,893 | 228,318 | 389,370 | 269,873 |
| | 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% |
| 2 | Classic | 3 698 243 | 1 779 040 | 887,578 | 961,543 | 5,930 | 4,447,600 | 116,741 | 199,089 | 357,449 |
| | 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% |
| 3 | Classic | 6 983 215 | 1 551 672 | 1,675,972 | 1,815,636 | 5,172 | 3,879,180 | 220,437 | 375,930 | 342,112 |
| | 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% |
| 4 | Classic | 7 422 051 | 2 288 929 | 1,781,292 | 1,929,733 | 7,630 | 5,722,323 | 234,289 | 399,554 | 73,658 |
| | 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% |
| 5 | Classic | 815 329 | 709 505 | 195,679 | 211,985 | 2,365 | 1,773,763 | 25,737 | 43,892 | 134,404 |
| | 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% |
| 6 | Classic | 450 633 | 502 500 | 108,152 | 211,985 | 1,675 | 1,256,250 | 14,225 | 24,259 | 500,000 |
| | 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% |
| 7 | Classic | 9 587 430 | 1 570 000 | 2,300,983 | 2,492,732 | 5,233 | 3,925,000 | 302,643 | 516,123 | 850,000 |
| | 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% |
| 8 | Classic | 2 586 987 | 955 025 | 620,877 | 672,617 | 3,183 | 2,387,563 | 81,663 | 139,266 | 31,739 |
| | 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% |
| 9 | Classic | 1 458 633 | 1 100 062 | 350,072 | 379,245 | 3,667 | 2,750,155 | 46,044 | 78,523 | 86,452 |
| | 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% |
| 10 | Classic | 7 421 986 | 2 632 000 | 1,781,277 | 1,929,716 | 8,773 | 6,580,000 | 234,287 | 399,550 | 793,000 |
| | 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% |
| 11 | 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 |
| | 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% |
| 12 | Classic | 9 782 365 | 4 747 812 | 2,347,768 | 2,543,415 | 15,826 | 11,869,530 | 308,797 | 526,617 | 797,161 |
| | 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 | |
| 13 | Classic | 4 256 921 | 2 752 326 | 1,021,661 | 1,106,800 | 9,174 | 6,880,815 | 134,377 | 229,164 | 528,648 |
| | 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% |
| 14 | Classic | 985 675 | 763 788 | 236,562 | 256,275 | 2,546 | 1,909,470 | 31,114 | 53,062 | 215,192 |
| | 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% |
| 15 | Classic | 5 578 710 | 3 457 030 | 1,338,890 | 1,450,465 | 11,523 | 8,642,575 | 176,101 | 300,321 | 746,000 |
| | 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% |
| 16 | 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 |
| | 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% |
| 17 | Classic | 6 498 753 | 3 102 042 | 1,559,701 | 1,689,676 | 10,340 | 7,755,105 | 205,144 | 349,850 | 0 |
| | 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% |
| 18 | Classic | 8 953 219 | 2 409 741 | 2,148,773 | 2,327,837 | 8,032 | 6,024,353 | 282,623 | 481,982 | 197,312 |
| | 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% |
| 19 | Classic | 9 814 867 | 2 709 286 | 2,355,568 | 2,551,865 | 9,031 | 6,773,216 | 309,823 | 528,367 | 713,681 |
| | 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% |
| 20 | Classic | 306 055 | 2 012 404 | 73,453 | 79,574 | 6,708 | 5,031,010 | 9,661 | 16,476 | 97,722 |
| | 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% |
| 21 | Classic | 2 236 916 | 3 121 271 | 536,860 | 581,598 | 10,404 | 7,803,178 | 70,612 | 120,421 | 1,004,981 |
| | 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% |
| 22 | Classic | 1 189 161 | 2 457 583 | 285,399 | 309,182 | 8,192 | 6,143,958 | 37,538 | 64,016 | 46,652 |
| | 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% |
| 23 | Classic | 626 666 | 1 295 101 | 150,400 | 162,933 | 4,317 | 3,237,753 | 19,782 | 33,736 | 163,108 |
| | 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% |
| 24 | Classic | 8 914 867 | 2 320 568 | 2,139,568 | 2,317,865 | 7,735 | 5,801,420 | 281,413 | 479,917 | 362,556 |
| | 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 CO₂ 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 CO₂ 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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