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Evaluating Environmental Impact in Foundations and Structures through Disaggregated Models: Towards the Decarbonisation of the Construction Sector

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Abstract: Having a tool in Spanish regulations to evaluate the sustainability of the construction process in a simple and efficient way (Annex 13 of the Structural Concrete Instruction EHE-08) means an advance with respect to regulations in other countries. However, the complexity of homogenising the conditions that affect the execution of each structure, which are of a very heterogeneous and variable nature, in order to be able to evaluate their contribution to sustainability within the same reference framework, is the greatest obstacle and can have a great influence on the representativeness of the obtained results. However, there are variables that, given their specificity and nature, are not contemplated in this methodology (dust, noise and vibration emission, transportation). This paper proposes a complementary disaggregated model to evaluate the sustainability of variables that are not considered, namely the transportation of materials to the worksite, the commute of workers, the construction process, the emissions of dust, noise and vibrations, as well as the necessary load tests. The results of the application of this model to the real case of the foundations of two singular buildings, show the importance that these previously unexamined variables can have when choosing the most sustainable technical solution in terms of CO_2 emissions.

Keywords: CO_2 emissions; disaggregated model; dust; noise and vibration emission; environmental impact studies; foundations and structures; sustainability; transportation

1. Introduction

Understanding the concept of sustainability is the first step in the study and analysis of the current tools used to evaluate environmental impact at a very reduced scale, which includes structures and foundations in general, and in particular those developed in urban areas since construction sites constitute major sources of pollutants provoking negative impacts on the environment [1]. In comparative terms, sustainability is a broader concept than that of sustainable development, since it can be applied effectively to scales below the regional level, as well as to products, processes and services. Therefore, sustainability is applicable to different levels or objects, such as a certain sector, a specific activity, a product, a process, a group or an entity. In this context, Badi et al. conduct a thorough review on the sustainability agenda in the construction sector [2] while Ahmad researches empirical interactions among the construction sector, energy consumption, urbanisation and carbon emissions [3]. In fact, the building sector in general has shown increased interest in environmental initiatives [4].

A first approach to the quantifiability of sustainability can be obtained from the use of indicators. Note that environmental indicators are not strictly indicators of sustainability. They indicate the state and changes of the environment; but they must also indicate the state and changes of the human system in relation to the natural system [5]. Environmental indicators can be applied in a simple way to specific dimensions of sustainable development, such as economic sustainability, or in a complex manner, bringing together ecological, social and economic elements into the concept of comprehensive sustainability [6]. However, sustainability indicators have been designed to condense complex information into signals and are able to selectively support polarised sides of the same debate [7].

Among all the studied indicators, those that are considered to be applicable are worth highlighting, such as the Life Cycle Assessment (LCA) and the Ecological Footprint (EF) [8]. In general terms and classified by levels, depending on the country of origin, there currently are commercial tools based on the LCA that are specific to building (Athena Estimator, Catalog Construction CH, Metabase, OFEN, etc.), tools for the evaluation of materials and building solutions (Athena Estimator, LCAid, Legep 1.2, Lisa, Metabase, TCQ2000, etc.) and tools to certify the global sustainability of a building during its occupation stage (BREEAM, CASBEE, Enlace, GBTool, Green Globes, LEED, Verde, etc.) [9].

The LCA encompasses the full cycle of the product, process or activity, taking into account the stages of extraction and processing of raw materials, production, transportation and distribution, use, reuse and maintenance, recycling and its final disposal [10–12]. It is a design tool that researches and evaluates the environmental impact of a product or service during all of the stages of its existence: extraction, production, distribution, use and end of life (reuse, recycling, recovery and disposal of waste), making it particularly difficult to apply at such a small scale [13].

On the other hand, geotechnical engineering explores new ways of sustainable work for the coming years, based on the increasing importance of energy saving and carbon dioxide reduction, based on a better study of the behaviour of materials, analysis of the site and the development of the design process [14], such as energy foundations and other thermoactive structures, where the concrete elements in contact with the ground, which are necessary for structural reasons and work simultaneously as heat exchangers, contributing to the protection of the environment and providing significant long-term savings as a result of reduced maintenance costs [15]. Similarly, other emerging fields of research such as the consideration of the soil as a living ecosystem, show enormous potential for innovative and sustainable solutions to the different geotechnical problems that arise in the field of foundations and structures [16].

Regarding the problem of scale, some research studies carried out by the University of Seville establish methodologies that allow the evaluation of the ecological footprint applicable to the residential building sector at the regional level [8] and at an international level [17], focusing on the urban scale, without extrapolating their results to the scale of building construction.

The particularities of the construction process complicate the definition of the units of measurement of the indicators. Time becomes a fundamental factor and it conditions the hypotheses that must be taken into account at this level of scale. The time factor is understood here as the time for the execution and implementation that conditions the potential sources of CO_2 emissions (dust, noise, vibrations, greater or lesser need for labour and therefore transportation, materials, etc.). At this scale, the partial execution time of any technical solution is one of the aspects to be taken into account in the decision making process, and the effects on the environmental impact of these are almost never taken into account.

In the field of foundations, in general, and in particular when it comes to the improvement of the terrain, project designers should incorporate the goals of sustainable development in their designs focused on soil improvement and construction methods, through the quantitative evaluation of the environmental impact.

At this scale, where most of the structures and foundations of buildings in urban environments are designed and executed without any type of sustainability requirement, it is necessary for them to incorporate previous evaluations such as the one included in Instruction EHE-08. The application of these evaluations is not currently mandatory. The application of these evaluations is not currently obligatory. In the future and in future revisions of this Instruction, it should incorporate the mandatory nature of the sustainable evaluation of the implemented building solution, incorporating the variables that are currently not taken into account as established in this research, and establish control tools in the case of changes in the solutions planned and evaluated in the project phase.

Simplified models for the evaluation of emissions and energy allows the estimation of the incorporated energy during the life cycle and the CO_2 emissions during the design process, which allows us to take into account the effects that soil improvements have in the environment [18,19].

On the other hand, regarding structures and foundations in Spain, Annex 13 of the Spanish Structural Concrete Instruction (EHE-08) incorporates a methodology that allows us to the evaluate the so-called Index of Contribution of the Structure to Sustainability (ICSS, ICES in Spanish). This methodology corresponds to the Integrated Value Method for Sustainable Assessments (IVMSA, MIVES in Spanish), developed by a multidisciplinary group led by the Polytechnic University of Catalonia, LABEIN-TECNALIA and the University of the Basque Country. This index is obtained from various parameters pertaining to the three basic levels of sustainability: environmental, social and economic, and it determines the structure's contribution to sustainability. From an environmental point of view, we must look to the Environmental Sensitivity Index (ISMA in Spanish), which measures the decrease in the usage of natural resources and the emission of pollution, and energy saving and recycling, among other aspects. Regarding social and economic sustainability, workers' training and safety are taken into account, as well as the application of new research findings or the extension of the life cycle of the structure, among others [20]. At the urban planning level, the urban resilience index provides a socio-ecological perspective to favour more sustainable, resilient and liveable cities in the 21st century [21].

The tools for the quantification of the usage of resources and CO_2 emissions produced in construction [9], along with the current development of tools based on this same principle, provide possible pathways for the quantitative evaluation of the level of emissions, a resource that can be used by anyone involved in the construction process [20]. In this context, other research shows a method to calculate a sustainability index that helps the decision-making process by quantifying the environmental impact of all the different alternatives that are commonly chosen in the installation of underground service infrastructure [22]. As a matter of fact, infrastructure works produce a high environmental and social impact mainly due to the pollutant emissions from heavy equipment [23,24]. Moreover, weight indicators of materials and resources are commonly used by transportation infrastructure rating systems to quantify sustainability [25]. In this regard, Paschalidou et al. assess air quality in metro-railway construction works in Greece [26].

Other studies done at a smaller scale within the structural building process focus on the placement of concrete [27]. They allow us an estimated quantification of the energy consumption and CO_2 emissions that result from the preparation of concrete in the plant, the transport of fresh concrete in concrete mixers, pumping on site and vibrating. Said estimate is based on the technical information given by the manufacturers of the equipment; this allows us to evaluate the impact of concrete structures. On the other hand, Luo et al. compares precast and in situ cast piles from GHG emissions life cycle [28] whilst Li et al. explores on-site industrialisation to improve sustainability towards a cleaner form of production [29].

Due to the particularity of their features and special circumstances, the application of the methodology mentioned in Annex 13 of the EHE-08 to singular foundations in general, and in particular to the lowered foundation of the Cilíndrico and Casa del Coronel buildings during the construction of the new Faculties of Law and Labour Studies of the University of Seville in 2007 [30], allows us to identify certain aspects or variables that where not examined and that may be of special importance when it comes to determining the contribution of their structures or foundations to their sustainability; these variables range from the transportation of materials, the workers' commute, the construction process, temporary traffic diversions, to joint emissions of dust, noise and vibrations; the variables also include carrying out the mandatory load test, as is required by law in most cases [31].

This is a completely pioneering building solution due to the difficulty stemming from the interference with the works execution of the subway line.

This action is very representative in two aspects which are not contemplated in the ICSS, such as the temporary traffic diversions (which were carried out in a sustained manner over time, and as shown in the research, may have had special impact for or against the sustainability of the implemented solution) or the load tests to be carried out given the special characteristics of the adopted solutions (bridge-type foundation). The University of Seville was the promoter of the works developed in this paper and the author of said paper participated actively in their execution, as the project manager.

The disaggregation of the construction process is essential to establish tools that allow us to evaluate the contribution of structures and foundations to sustainability. In the aggregated models, as is the case of the IVMSA methodology, a single value is set for all the parameters of the model. Therefore, the model predicts outputs for the provided inputs without reporting what takes place within the system (obtaining a certain level of sustainability according to the method). However, the disaggregation of the construction process at the required scale (structure and foundations) allows us to research the specific conditioning factors of the construction process, along with its relationship with the environment in which it is located. Sandanayake et al. develop a methodology based on an analytical hierarchy process to weight materials, transportation and equipment carbon emissions in regard to five impact categories: Global Warming, Photochemical Oxidant Formation, Acidification and Eutrophication Potentials, as well as Human Toxicity [32].

Despite the fact that the methodology proposed in Annex 13 of the EHE-08 signifies an important advance in the incorporation of sustainability criteria at the project level and regarding concrete structures compared to other countries' regulations, some deficiencies have been detected, which should be addressed, as there is scarce research in this area. One of the few examples can be found in a Martinez et al., who propose a multi-objective genetic algorithm optimisation method to assess road and infrastructure construction processes minimising carbon emissions, embodied energy and economic costs [33].

We can find references to singular interventions in the foundations of buildings in cases where emergency situations took place, such as those produced by earthquakes, which have put evaluation protocols into place [34] or processes for decision-making in later works [35]. More research has been done when foundations affected by settlements have been in need of repair [36–39], some of which have meant a leap forward in the study of techniques, processes, solutions and results in real cases [40]. Aspects such as intervention on site, derived costs, or the restoration of buildings in situations of social emergency, have also not been extensively researched or at least not disseminated, given the reluctance to publish technical data that may be liable [40]. In general terms, this means that technicians who face situations of this type do not have references on which to base their decisions and that, in these scenarios of uncertainty, conservative and oversized solutions are preferred, for reasons both economic and technical. A notable exception can be found in Pineda et al., who performed an environmental and structural assessment of strengthening works in a Spanish church [41].

In this paper, the University of Seville aims to disseminate to the scientific community the research done during the construction works carried out in the practical case, just as it did with the foundation repairs in 40 homes in the "RENFE" neighbourhood, whose foundations were affected by the adjacent excavation of the new Faculty of Medicine. A standard model has been created by this research for its use in similar situations from the perspective of sustainability [42].

The main goal of this paper is to formulate a disaggregated model for the evaluation of the environmental impact of building solutions for structures and foundations (CDM-SABSSF), which allows for a global quantification of their sustainability, considering and consequently complementing any variables not examined in the methodology proposed by EHE-08. Neither the methodology proposed in the model that we reference in this paper nor the complementary one proposed in our research are based on LCA.

The application of the methodology proposed in the model will in turn pave the way to international regulations and laws pertaining to the design and building of concrete-made elements; among them, Eurocode 2, applicable in European Union member states, which does not include a section on sustainability criteria during the design phase. The ACI-318-14 standard in the US, the CIRSOC-201-2005 regulation in Argentina or the SP63.13330.2012 standard in Russia.

The proposed methodology is tested by applying it to a real case study, in order to contrast the obtained results if it were applied, considering the model proposed in this research.

The case study shows that the sustainability of a building solution can change depending on the indicators or analytic tools used.

2. Materials and Methods

The diversity of possible building solutions or methods for structures and foundations according to their type, operation and procedures for their implementation is one of the main reasons to propose and define a new model to complement the information obtained after determining the index (ICSS). This model, which complements the one established in Annex 13 of the aforementioned regulation, constitutes an independent tool for the objective assessment of the sustainability of construction solutions or methods in the structures and foundations phase, in order to guarantee a unique and homogeneous comparative framework within the reach of all the agents involved in the building process. For the development of the methodology brought forward by this paper, we need to develop an overview of the index (ICSS) and its scope, as well as any variables not considered in accordance to the required scale. This index focuses on the three approaches to sustainability (environmental, social and economic), with different scopes and criteria depending on the case. In the attached figure (Figure 1) we can see the scope of the methodology of the Integrated Value Model for Sustainable Assessment (IVMSA, MIVES in Spanish), on which Annex 13 of -08 is based, as well as the unrelated aspects that hold relevance in the case of single foundations.

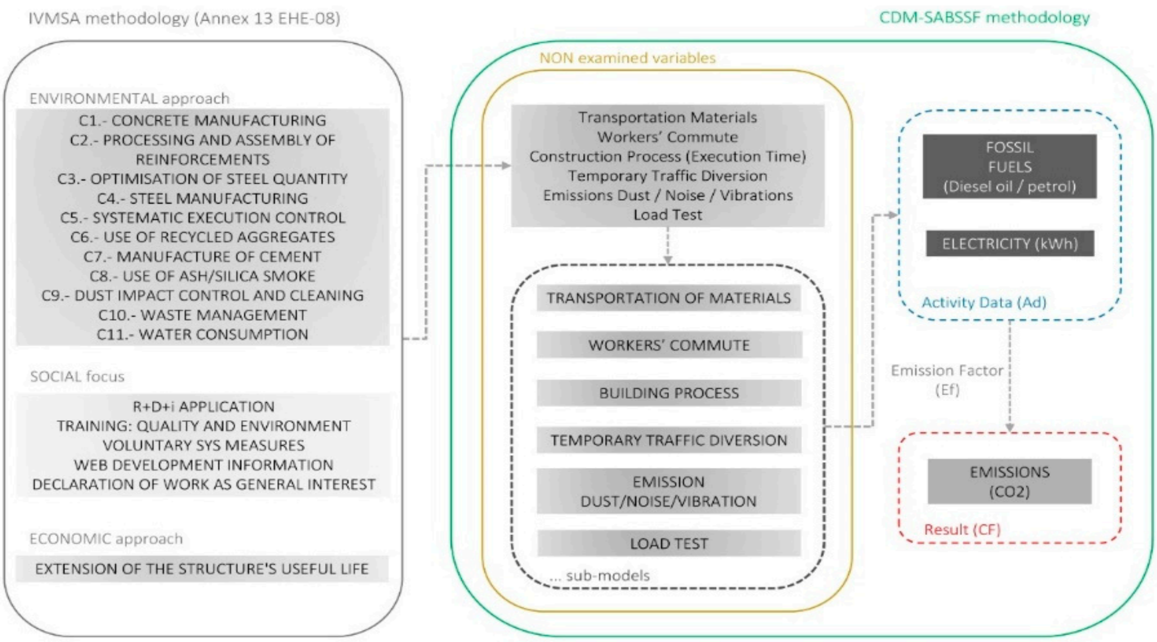


Figure 1. IVMSA methodology, Non Examined Variables. Methodological Basis CDM-SABSSF.

The aim of this paper is not to go into detail regarding the IVMSA methodology on which the ICSS (value added) is based. Also, the fact that IVMSA is included in the Spanish Instruction does not prevent it from being applied as a method for the evaluation of the sustainability of structures and foundations in other countries. In fact, the methodology proposed in this paper (CDM-SABSSF) complements the decision making process derived from obtaining the ICSS, and can be applied in any structural area (national and international).

It is worth noting that with regards to the unidentified aspects and the required scale, the building activity and the construction process at this level in general present homogeneous patterns regarding energy consumption (electric and fossil fuels) and the use of manpower. There is a clear relationship between unrelated aspects and the use of energy resources. However, in some of them, as is the case of noise and vibrations, this relationship is much more difficult to establish.

The proposed model uses an indicator that has been sufficiently contrasted by the Spanish Climate Change Office [43] easy to use, and applicable to all agents involved at this scale. The carbon footprint, which will allows us to know the energy consumption levels that are predominant in this evaluation phase, identifying the amount of GHG emissions that are released into the atmosphere (expressed in CO_2eq) as a consequence of the development of said activity, the work execution of the foundation or structure of a building, using Formula (1); understanding by "manufactured product" in situ the manufacture of a product from elements and materials through a system that allows it to be built through the use of necessary auxiliary and human means with the required technical capacity.

$$\text{Carbon Footprint (CF)} = \text{Activity Data (Ad)} \times \text{Emission Factor (Ef)} \quad (1)$$

in which: Activity data (Ad) stands for the parameter that defines the degree or level of activity that generates GHG emissions. The emission factor (Ef), refers to the amount of GHG emitted by each unit of the parameter (Ad).

At this scale, we consider the data generated from the transportation of the factory, main suppliers of concrete, steel and hot-rolled steel, to carrying out the load test, including the auxiliary and personal means necessary to implement said activity according to their technical attributes and design.

The proposed model and its scope, named as Disaggregated Model for the Sustainable Evaluation of Solutions in the Structures and Foundations phase (CDM-SABSSF in Spanish), requires the development of different sub-models according to the nature of each of the "non examined variables" (by annex 13 of the EHE-08) which constitute the focus of this research, based on the disaggregation of the building process. It allows us to establish and accurately discern the specific singularities of each of these variables that remained unexamined, in order to integrate the most appropriate variables and elements in each sub-model, which will constitute the methodological basis of the model that is developed below (Figure 1).

Based on this general approach, each sub-model must establish the mechanisms and tools to determine the representative activity data (Ad) according to the nature of the unexamined variables, in order to obtain the level of CO_2 emissions from the corresponding conversion factors (Ef) as appropriate. The activity data that should be obtained, in accordance with the goals of the model, are based on the quantity of fossil fuels and electricity consumed during the work execution process according to the technical solution adopted in each of the scenarios considered.

Independently from the specific sub-model that would be considered along with its particularities, we can set the emission factors associated with fossil fuel consumption included in the above-mentioned guide as a reference tool [43], due to its simplicity and easy application by the agents intervening in the construction process.

With respect to emissions associated with energy consumption, the emissions data provided by the electric company during the time period corresponding to the study, or the data provided by the Ministry of Agriculture, Fisheries and Food [44] should be applied.

Regarding the practical applications of this model, we have considered the period of works execution of the mentioned works (2007) and the data corresponding to the electric company (ENDESA ENERGÍA, S.A.) and to the joint venture of the construction companies (FACULTADES UTE) that led the works execution during the construction of the foundations that we are analysing. Shown below are the emission factors considered with respect to the usage of fossil fuel (Table 1) and electricity usage (Table 2), respectively.

Table 1. Fossil Fuel Emission Factors.

Fuel	Emission Factor (Ef)	
Petrol	2.196	kg CO_2/L
Diesel A	2.471	kg CO_2/L
Diesel C	2.786	kg CO_2/L
Generic LPG	1.656	kg CO_2/L
Gas	0.202	kg CO_2/kWh
Butane Gas	2.964	kg CO_2/kg
Propane	2.938	kg CO_2/kg
Fuel Oil	3.054	kg CO_2/kg
Coal (National)	2.300	kg CO_2/kg
Coal (Imported)	2.530	kg CO_2/kg
Petroleum Coke	3.195	kg CO_2/kg

Table 2. Energy Sources (ENDESA ENERGÍA, S.A) and Emission Factors for Electricity (2007).

Source	Endesa Energia, S.A
Renewable (Pure + Hybrid)	27.70%
High Efficiency Cogeneration	2.00%
Cogeneration	6.20%
Coal	22.50%
Fuel/Gas	3.20%
Nuclear	16.80%
Others	0.90%
Ef CO_2 (kg CO_2/kWh)	0.37

3. Development of the Disaggregated Model

Based on the proposal of the general model, we must establish the different sub-models for each of the "non examined variables" in order to obtain the activity data needed to determine the carbon footprint, after applying the corresponding emission factors.

3.1. Transportation of Materials

The materials that pertain to this specific phase (foundations and structures) are mainly fresh concrete, corrugated steel and formwork material. In order to determine the fuel consumption associated with the transportation of the necessary materials, we take into account the data provided by the Ministry of Development [45], which determines the average fuel consumption calculated for the most common types of vehicles used to transport goods (Table 3), which allows us to evaluate the CO_2 emissions produced during the transportation of materials from factories to the building site.

The sub-model proposed to determine the volume of emissions derived from the transportation of materials is based on the following expression (2):

$$E_{TM} = \sum_{i=1}^{n}\left[\left(\frac{W_i}{LC_i}\right)\cdot D_i \cdot C_i\right]\cdot Ef_i \quad (2)$$

where W_i represents the weight of the material to be transported, LC_i the load capacity of the type of vehicle considered, D_i the distance between the factory or distribution centre and the building site, C_i the energy consumption associated with the type of fuel used and Ef_i the emissions that corresponds to each of these.

Table 3. Average Fuel Consumption f or Vehicles Transporting Goods.

Specialty	Vehicle Type Analysed	Consumption [1] (L/100 km)
General Cargo	Articulated Vehicle 3-axle vehicle 2-axle vehicle	36.5 28.0 26.0
Chillers [2]	Articulated Vehicle 3-axle vehicle	36.5 26.0
Tanks transporting Hazardous Goods: Gas/Chemicals/Food/Powder	Articulated Vehicle	36.0
Carrier	Road Train	42. 0
Industrial Carriers	Road Train	48.0
Road Train	2-axle vehicle + 3-axle Trailer	40.0
Container/Bulk	Articulated Vehicle	36.5
Works	Articulated Vehicle	40.0
Livestock Transportation	3-axle vehicle 2-axle vehicle	28.0 26.0
Concrete mixers	3-axle vehicle 4-axle vehicle	64.0 66.0
Intermediate Vehicle Van– 2 Axles Van	2-axle vehicle 2-axle vehicle	20.0 12.0

[1] Referring to fuel consumption of Type A diesel; [2] Not including fuel consumption for the cooling unit = 3–4 L/h (additional).

3.2. Workers' Commute

In order to objectively determine the CO_2 emissions derived from the displacement and commute of workers during the execution of the foundations and structures, due to the specificity of the work and the sectorial grouping of its workers from the geographical area, we establish the sub-model based on the knowledge of the subcontracting companies that develop them; as well as their execution time. The real data obtained will be determined by the type of vehicle, fuel used and the number of occupants, based on the following Formula (3):

$$E_{DT} = \sum_{i=1}^{n} [T_i \cdot D_i \cdot C_i] \cdot Ef_i \tag{3}$$

where T_i represents the number of trips necessary for the commute of the workers, D_i the distance between the workers' place of residence, C_i the energy consumption depending on the type of fuel used and Ef_i the corresponding factor of emission.

The electricity consumption by workers during breaks for breakfast, lunch and activities carried out after the end of the working day (lights, use of microwaves, hot water heaters for showers, etc.) is not taken into account, due to the heterogeneous nature of these factors and their lack of repercussions.

3.3. Construction Process

Any building solution implies the use of human resources (workers), a series of additional means and specific techniques that determine the runtime of a building unit. The consumption of fossil fuels by the human resources (site personnel and workers) has been taken into account in the previous sub-model.

The differential element of these "non examined variables" is the use of additional machinery associated with a specific construction method, which will involve a level of consumption of fossil fuels and electricity energy depending on the hours of use of the machinery (tower cranes, mobile cranes, small, manual machinery, etc.). The data on actual consumption of this additional machinery is determined by the manufacturer or by the Association of Infrastructure Construction and Concession Companies (SEOPAN in Spanish) [46], which allows us to determine the main and secondary energy consumption depending on the type of fuel and the power allocated to the additional machinery, as shown in the table below (Table 4).

Table 4. Main and Secondary Energy Consumption: Construction Machinery (Source: SEOPAN, 2008 [46]).

Main Energy Consumption		Secondary Energy Consumption
Diesel oil (L/h per kW)	0.15–0.20	15% of the main energy consumption
Petrol (L/h per kW)	0.30–0.40	8% of the main energy consumption
Electricity (kWh per kW)	0.60–0.70	5% of the main energy consumption

The following formula represents the proposed sub-model to determine the volume of emissions associated with the construction process (4):

$$E_{PC} = \sum_{i=1}^{n} [(T_i \cdot D_i \cdot C_i) + (H_i \cdot C_i)] \cdot Ef_i + \sum_{j=1}^{m} \left(H_j \cdot C_j\right) \cdot Ef_j \tag{4}$$

where, in the case of fossil fuels, T_i represents the number of trips necessary for the return trip of the machinery in question to and from the construction site, D_i the distance to transport the machinery from the company's facilities, C_i the energy consumption associated with the type of fuel used, H_i the hours of usage of the machinery and Ef_j the emission factor corresponding to the consumption of fossil fuels, while H_j represents the hours of use of machinery running on electricity, C_j represents their electricity consumption and Ef_j represents the emission factor corresponding to electric energy consumption.

3.4. Temporary Traffic Diversions

Provisional traffic diversions in civil engineering projects related to road transportation infrastructure are in themselves one of the most important variables to be taken into consideration during the execution phase of the works. However, this is not the case for construction works in urban environments. Approaches aimed at assessing the environmental impact that these traffic diversions may have in urban environments are rare, and said measures do not necessarily result in a negative impact on CO_2 emissions.

A provisional traffic diversion that requires less commute time will result in a lower consumption of fossil fuels by regular users of the affected route, constituting a reduction in the usual levels of CO_2 emissions from an environmental point of view, as has been shown in the period of confinement caused by the COVID-19 pandemic, in which cities have reached the lowest level of CO_2 emissions in 50 years.

In addition to the length of the route, it is essential to assess the traffic levels in the routes affected by these diversions in order to determine average fuel consumption in accordance to the vehicles that are taken into account.

Average Daily Traffic (ADT), defined as the total number of vehicles that have passed through a section of a road during a given year divided by 365 days, is the most commonly used index to assess traffic volumes on urban and interurban roads. The data can usually be obtained from local traffic agencies. Once the affected traffic has been assessed and the time period had been estimated, the greater or lesser level of emissions derived from the consumption of fossil fuels can be established, during the period in which the traffic diversions exist, according to the following Formula (5):

$$E_{DPT} = \sum_{i=1}^{n} [L \cdot N_i \cdot T_i \cdot C_i] \cdot Ef_i \tag{5}$$

where L stands for the length travelled by the vehicles affected by the traffic diversion (and which may be greater or less than the originally intended length), N_i the number and type of vehicle affected (obtained from a previous assessment of the traffic) T_i the effective duration of the provisional diversion, C_i the energy consumption associated with the type of fuel used and Ef_i the corresponding emission factor.

3.5. Dust, Noise and Vibrations Emissions

Any specific activity of the scale mentioned in this research involves a joint emission of dust, noise and vibrations to the immediate environment. The need for tools that allow us to evaluate this impact in a global, simplified way and within the reach of all the agents intervening in the process, has prompted us to propose a model that is somewhat ambitious in order to be able to determine an order of magnitude that is sufficiently representative and that in turn allows us to establish a comparison in homogeneous terms with the results obtained in the evaluation of other non examined variables. In other words, it is very difficult to establish a single quantitative variable that allows us to determine, with a sufficient degree of representativeness, the effects produced by the joint emissions of dust, noise and vibration.

With regards to the joint effect that is produced by certain construction works (emission of dust, noise and vibrations) it should be noted that, among others, the typical reaction of people who carry out their activity in nearby buildings (such as homes, work or education centres, etc.) consists of "closing the windows" as a response to dusty and noisy environments (or even vibrations). Such a common action, which is the go-to response of any citizen in this type of situation, can lead to considerable variations in the patterns of use and operation of air conditioning systems at certain times of the year. These variations in the energy consumption patterns of air conditioning and heating systems is linked to a variation in the consumption of electricity and by extension, in the level of CO_2 emissions associated with it. In short, there is a more direct relationship between dust and noise emissions (and to a lesser extent, vibrations) and CO_2 emissions.

The proposed sub-model is based on the main variable involved in the effects generated by the emission of dust, noise and vibrations, which is related to the distance or proximity of the buildings near the area where the construction works are taking place. In general terms, the hypothesis that we establish explains that the levels of dust, noise and vibrations that are created affects the first proximity radius (first level of buildings surrounding the location of the construction works), since the following rings are protected by the first level, which acts as a protective barrier against said emissions.

Conversely, once the number and composition of the buildings that make up the proximity ring has been determined, it is necessary to assess them based on the available data (type of building, type of housing and commercial premises, percentage of occupancy and use, opening hours, nature of the indirect services, etc.) in order to be able to determine the percentage of air conditioning equipment to be considered in the calculation. The assessment of air conditioning demand can be extracted from data provided by the Institute for Energy Diversification and Saving (IDAE in Spanish) [47], which establishes the values of reference to be taken into account with regards to the demand for heating and air conditioning by surface area in different Spanish cities.

Another central aspect of the sub-model is undoubtedly the runtime of execution of the works and the time of year to be considered, which has a direct proportional effect on the summer season (increased need for air conditioning), and to a lesser extent in autumn and spring depending on the area under consideration. For this reason, it is necessary to consider a coefficient of effect that takes into account the time of execution of the works in the different seasons of the year. The sub-model proposed to determine the volume of emissions associated with these variables corresponds to the formula below (6):

$$E_{PRV} = \sum_{i=1}^{n} [DA_i \cdot IC_i \cdot T_i \cdot CL_i \cdot CEA_i] \cdot Ef_i \quad (6)$$

where DA_i stands for the affected demand or air conditioning and refrigeration needs corresponding to each household or property affected (primary ring), IC_i the percentage of increase in energy consumption considered over the affected demand associated with the action of "closing windows" and therefore to be considered as net needs for the overall calculation of emissions, T_i the works execution period, CL_i the length coefficient to calculate the greater or lesser proximity of the property to the centre of the emissions, CEA_i the specific activity coefficient that takes into account the specifics of the activity carried out in the property in question and Ef_i corresponds to the emission factor.

3.6. Load Test

The sub-model proposed to evaluate the volume of CO_2 emissions derived from the necessary activities that must be carried out during the mandatory load test depends to a great extent on the type of tests to be performed and may be very different if we consider load tests on foundations or on structures at slab level, where the needs and the means to be used are radically different depending on the case (buckets with water, extraction of cores in the case of structural rehabilitation and reforms, non-destructive tests, etc.).

In this regard, we have focused on the specific conditions for a unique foundation, such as the one in the case study mentioned in this paper, a shored foundation, where the load test consists of carrying out four static load assumptions by using 4-axle trucks loaded with a maximum total weight, including tare, of 40 T and carrying out a dynamic load test consisting of the transit of one of the trucks on a standardised board in order to induce a vibration in the foundation and thus determine the fundamental frequency of vibration of the foundation. The proposed sub-model, which would also be valid for the types of load tests carried out in the case of road bridges, allows us to determine the volume of emissions according to the following expression (7):

$$E_{PPC} = \sum_{i=1}^{n} [(T_i \cdot D_i \cdot C_i) + (H_i \cdot C_i)] \cdot Ef_i \tag{7}$$

where, in the case of fossil fuels, V_i represents the number of trips necessary for the return journey of the vehicles and machinery used, D_i the transport distance between the premises of the company that owns it and the building site, VT_i represents the number of trips needed for carrying out the test, DT_i the internal distance travelled during the execution of the test, C_i the energy consumption associated with the type of fuel used, H_i the hours of usage and Ef_i the emission factor corresponding to the consumption of fossil fuels.

4. Applications of the Case Study

In this section, we proceed to apply the proposed model to a real case study. A specific case that had a great social and economic impact: the works carried out on the foundations of the Edificio Cilíndrico and the Casa del Coronel, during the execution of the works for the new Faculties of Law and Labour Studies of the University of Seville, that took place between 2005 and 2008 in said city.

The case study was selected because it represents a unique opportunity to obtain research knowledge and to serve as an example for other similar cases that may arise in the future when faced with a similar real case that may take place.

This is a totally pioneering solution where two entire buildings needed to be completely shored due to the interference with the execution of the construction works in the subway line, instead of being demolished for the subway line to run through that space.

During the construction of both buildings, Line 1 of the Seville subway system was also under construction. Many problems arose as the alignment of the subway's layout caused a diversion of the original line, which meant that the space allocated for the foundations of the two university buildings was invaded. Ferrocarriles Andaluces, which belongs to the Department of Public Works and Transport of the regional government (Junta de Andalucía), acting as the promoter of the works on Line 1 of the

Seville Metro subway system, decided that the line should pass right through emblematic buildings during their execution of works and rehabilitation phase; one of the authors of the current research participated in this process as head of production of the joint venture in charge of the execution of the works (FACULTADES UTE, in which FERROVIAL-AGROMAN, S.A. has a majority shareholding).

The building solution that was applied was a clear case of knowledge transfer to the production sector, and was resolved by the execution of an innovative foundation supported by these buildings to make it compatible with the transport infrastructure, so Line 1 of the Seville METRO subway system could cross right below these buildings.

The proposed model aims to show the possible improvements to be considered in similar cases from an environmental point of view, in order to seek initiatives that push for the decarbonisation of the construction sector, as a plan of action against Climate Change.

The building solution that was carried out to lay the foundations of both buildings over the subway tunnel was a pioneering solution in Spain, given the size of the buildings affected. It was an engineering challenge of great magnitude and it was based on the use of 35 pre-stressed double "T" beams with edges of varying length depending on the areas (2.00 m in the area of the Edificio Cilíndrico and 1.70 m in the area of the Casa del Coronel), arranged at the top, with an upper 60 cm slab of reinforced concrete acting as the compressed head of the set. The goal of this solution was to completely pile up the foundations of both buildings and preserve the subway's tunnel's original route (as seen in Figure 2).

Figure 2. Execution of the works on the Cilíndrico and Casa del Coronel buildings over the Seville subway line. Source: The authors.

The first step is based on a detailed study of the solution, based on the use of prefabricated double "T" beams (VDT solution), with special attention to the load test due to its special features and unique nature. The complexity of completely overhanging two buildings to preserve the METRO tunnel created the need to carry out a load test that would guarantee the adequate response of the structure under a load of this level.

With this in mind, we developed a finite element model of the VDT solution in order to be able to compare it with the aforementioned applied model (the one included in the load test project) and with the actual response of the structure during the test (according to the results included in the final reports issued by the laboratory that carried out the project). Figure 3 shows the finite element model made for the foundation, using the ANSYS program.

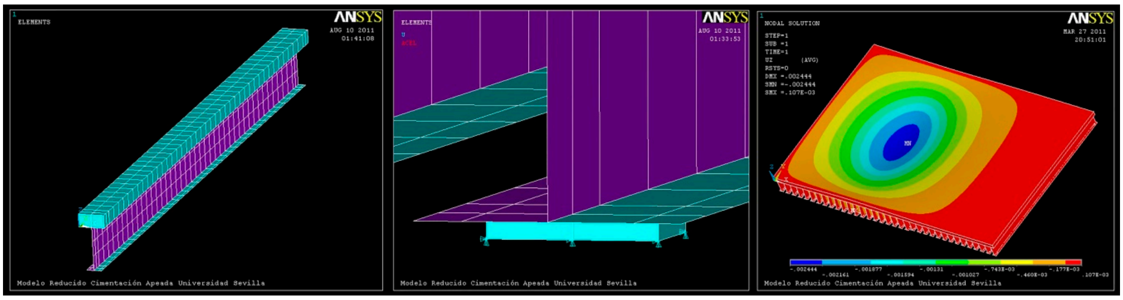


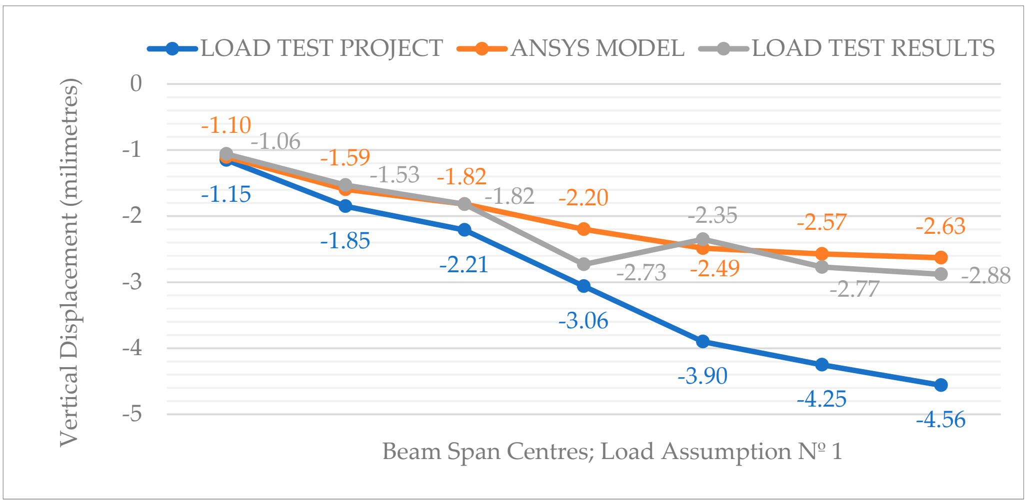
Figure 3. Foundation Model (ANSYS) – Simulation of a Static Load Assumption of the works on the Cilíndrico and Casa del Coronel buildings over the Sevilla subway line.

The figure, showed below represents the modelling of the double "T" beam, the upper slab and the support equipment (neoprene), as well as the simulation of one of the static load assumptions performed.

Regarding the load test, it is worth stressing that given the features of the loads in question (axle loads from the pillars), it was necessary to carry out four static load assumptions, combining the number and arrangement of fully loaded 4-axle trucks (total weight of 40 T) together with a dynamic assumption consisting of driving one of these trucks on a plank (standard RILEM-type), thus causing an excitation of the foundation board.

The instrumentation that was carried out consisted of the arrangement of different extensometers to measure the descents at the beam's span centres during the performance of the different static assumptions, as well as the arrangement of two accelerometers to record the vertical accelerations during the dynamic load assumption. In the case of the static load assumptions, represented in the following figures (Figure 4), the decreases measured at the span centre of the beams can be compared, together with the results of the model included in the load test project, and the model that was performed in this paper for the VDT solution, which is the one that was actually implemented.

The results clearly show that the developed model is much closer to the real response of the structure (greater convergence of results when comparing the decreases in the real case and those obtained in the ANSYS model), and where the response of the model included in the load test project is much less rigid than the real case. The divergence observed in static load assumption No. 1 (Figure 4a) is especially noteworthy.



(a)

Figure 4. *Cont.*

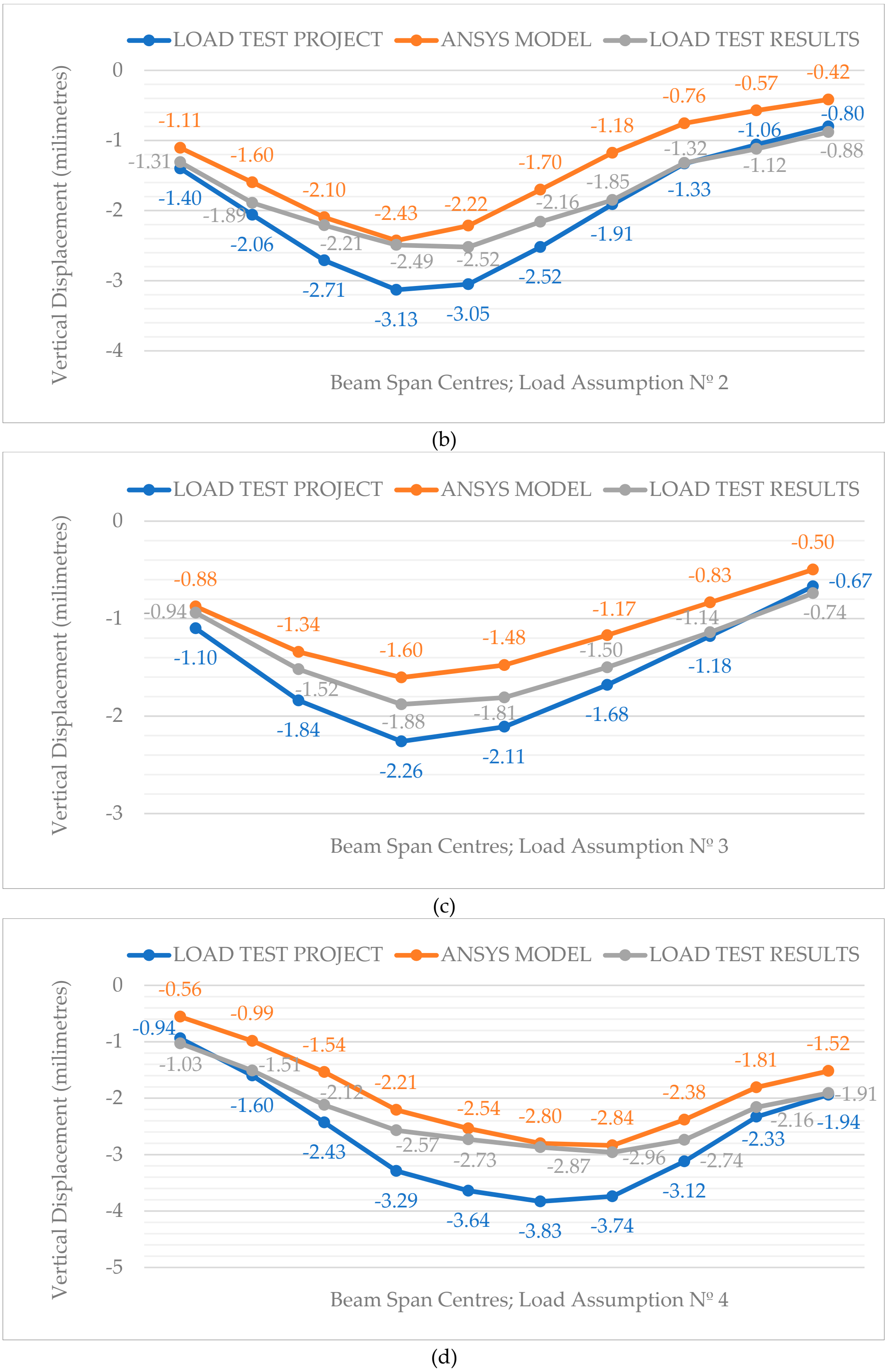


Figure 4. Vertical Displacements in Beam Span Centres; Load Assumptions Nº1, Nº2; Nº3 and Nº4. (**a**) static load test hypothesis Nº1; (**b**) static load test hypothesis Nº2; (**c**) static load test hypothesis Nº3; (**d**) static load test hypothesis Nº4.

Secondly, a study is carried out to explore other technically possible alternatives to the implemented building solution (VDT). Among the examined alternatives, three different solutions are selected and developed: firstly, two solutions based on the use of tamped beams; and a third one based on the use of post-tensioned concrete (HPO Solution). Regarding the solutions based on the use of tamped beams, the first to be considered is a solution with 1.50 metre-high beams and a 60 cm upper slab (VAR1 solution), and secondly another solution with 1.70 metre-high beams and a 30 cm upper slab (VAR2 solution) is considered.

Once the various alternative solutions have been established, the needed resources (machinery, materials and labour) are evaluated for each case. Subsequently, the methodology described in EHE (Annex 13) is applied to the four proposed scenarios. The Structure Contribution to Sustainability Index (ICSS) is obtained for each of the solutions studied (VAR1, VAR2 and HPO), obtaining similar results (Table 5) corresponding to the same sustainability interval (Level "D"). It should be noted that the methodology applied establishes five levels of sustainability, from Level "A" (more sustainable) to Level "E" (less sustainable), with regards to the structure's contribution to sustainability.

Table 5. Compared Index of Contribution of the Structure to Sustainability (ICSS) index for the foundation solutions considered.

Solution	ICSS	Level
VDT	0.37	Level D
VAR1	0.34	Level D
VAR2	0.35	Level D
HPO	0.24	Level D

As seen in the table, completely different solutions in terms of the type, operation and procedures for their implementation have obtained the same level of contribution to sustainability. This gives us reasons to define a model that allows for the complementing of the information obtained after determining the aforementioned index (ICSS), which should influence those variables not contemplated in the applied methodology, which could be constituted as an independent tool for the objective evaluation of the sustainability of a certain solution in the structures and foundations building phase.

Once the sub-models have been defined, corresponding to each of the non examined variables, the model is applied to the solution that was implemented in the case study: prestressed double "T" beams (VDT) as well as for the technically viable alternatives studied, which are VAR1, VAR2 and HPO.

In order to apply the described methodology and to calculate the level of emissions, we have taken into account the data from supplier companies and subcontractors who carried out the works with the VDT solution, hypothesising for rest of the solutions that the supplier companies and subcontractors are the same.

Table A1 of Appendix A includes the general summary of the estimated CO_2 emissions after the application of the sub-model corresponding to each of the variables not examined in the proposed disaggregated model. A summary of this table is shown in Table 13, with the global volume of emissions calculated for each of the technical solutions considered in the case study.

4.1. Transportation of Materials

Regarding the transportation of materials, and according to the volumes required in each of the analysed solutions, the transportation of fresh concrete from the manufacturing plant to the building site, the transportation of rebar (in 12 m bars) from the distribution centres, and the formwork systems from the storage facilities specialised in this type of material have been considered. Specifically, and depending on the case, the transportation of the prefabricated beams (VDT, VAR1 and VAR2) from the plant to the building site has been taken into account, and, in a similar way, in the case of the solution based on the use of post-tensioned concrete (HPO), the transportation of the active reinforcement from the same distribution centres as that of the passive reinforcement has been considered. The results obtained are shown in the attached table (Table 6).

Table 6. Calculation of CO_2 Emissions: Transportation of Materials (E_{TM}).

Transportation of Materials	VDT	VAR1	VAR2	HPO
Transportation of Concrete	4.549	6.334	4.491	6.334
Transportation of Prefabricated Beams	1.163	6.286	6.286	-
Transportation of B500S Steel	0.025	0.034	0.017	0.067
Transportation of Formwork	0.038	0.077	0.077	7.162
[T CO_2]	5.775	12.730	10.871	13.563

4.2. Workers' Transportation And Commute

Depending on the type of solution and building works to be carried out, the preparation and assembly of rebar, the formwork and pouring of concrete, the collection, preparation and placement of prefabricated beams and, in the case of the load assumption with post-tensioned concrete, the assembly work of post-tensioned reinforcement (laying of sheaths, routing and pulling of cables, placement of wedges and clamps, as well as stressing with a hydraulic multi-screw jack); we have determined the works for the execution period and the number of operators needed.

In accordance with the grouping of each subcontractor company and its different geographical locations, different hypotheses have been established to determine the degree of occupation and type of fuel used in the vehicles necessary for each solution studied; to determine the movements of the workers from their places of residence or accommodation to the work site.

The results obtained after the application of the corresponding sub-model are shown below (Table 7) and as can be seen, the lowest volume of CO_2 emissions corresponds to the VAR2 solution.

Table 7. CO_2 Emissions: Workers' commute (E_{DT}).

Workers' Commute	VDT	VAR1	VAR2	HPO
Gasoline Vehicles	0.385	0.355	0.337	0.296
Petrol Vehicles	0.423	0.391	0.370	0.938
[T CO_2]	0.808	0.746	0.707	1.234

4.3. Building process

The first thing to be taken into account were the permanent auxiliary means that were already in the building site, namely the tower cranes to lift loads and move materials. To determine the level of emissions associated with their use, the variables considered where the time spent unloading materials (passive and active reinforcement and formwork) and the time corresponding to the operations performed, depending on the type of solution considered, during the execution of the works.

The electric energy consumption has been estimated from the total usage time. The average duration of the usual manoeuvre has been estimated at 15 min, increased by 5% (due to possible unforeseen events or special difficulties in loading and/or unloading). Bearing in mind that other works are carried out during the building process which are not strictly related to the foundation, a usage coefficient of 70% of the total time has been considered in the case of the assembly process of passive reinforcement and formwork in solutions based on the use of pre-stressed prefabricated beams (VDT, VAR1 and VAR2) and a coefficient of 80% in post-tensioned concrete (HPO) works including the assembly of passive reinforcement and formwork as a result of its greater complexity in terms of geometry and functionality.

Secondly, regarding the load test assumptions based on the use of large-sized prefabricated beams (VDT, VAR1 and VAR2), the operations corresponding to the lifting and placement manoeuvre have been taken into account. In this sense, in the double "T" pre-stressed beams (VDT) solution, a 400-tonne crane was used on the capping slab of the subway tunnel, while the use of two 200-tonne cranes has been considered for the trough-beams of the VAR1 and VAR2 solutions, due to their dimensions and weight.

As for the consumption of fossil fuels (diesel) associated with the use of this type of large cranes, it has been estimated that for road travel, average consumption (by manufacturer, type of engine and speed on the road) is 1.5 L/km for the 400-tonne crane and 1.0 L/km for the 200-tonne crane. The fuel consumption associated with the movement of the cranes from the facilities of the subcontractors that carried out the work has also been considered, as well as that of the internal transfers during the manoeuvre, based on the data provided by the different manufacturers and suppliers, adopting a value of 5 L/h of consumption during the operation.

Thirdly, within the construction process, the placement of concrete has been taken into account. According to the current available data and taking into account the distances from the point where the pump is placed and the upper slab of the foundation, the use of 42-metre range pumps has been considered to pour the concrete, with a power of 400 CV (294 kW) and an average pumped concrete output of 80 m^3/h (according to the times for the changes of concrete and vibrated trucks), according to the data provided by the Spanish Society of Concrete Pumps (SEBHSA) [48].

To calculate the consumption of the pumps during concrete pumping, taking into account a power of 294 kW for a 42 m pump, a diesel consumption of 0.15 L/h per kW has been considered, that is, a consumption of 44.1 L/h. A percentage increase of 5% has also been considered (to account for possible divergence) due to possible unforeseen events during the pouring of the concrete. Similarly, fuel consumption has been determined as a result of the movement of the pumps from their base to the building site.

A differential aspect in contrast with other types of works is the on-site workshop. In general, it is becoming less common for iron to be produced in on-site facilities where the works are taking place, since its manufacture is usually sourced out to workshops when the works exceed a certain size. This way, the shaping and use of steel is optimised, the processing costs are reduced and so is the transport of the processed elements to the building site.

In this particular case study, the production workshop was located on site, so we have calculated the CO_2 emissions generated during the production of the necessary passive reinforcements in situ, for each of the hypotheses put forward. They are the following: bending machine, cutting machine and stirrup bar, whose data are obtained from the general attributes of the machines (as seen in the documentation provided by manufacturers and usual suppliers of companies dedicated to the production and assembly of corrugated steel in the region of Andalusia) [49].

Regarding the commission of the works, and with a lower comparative value, there is the use of concrete vibrators during the pouring of the concrete. In this case, we have considered the use of common single-phase universal electric needle vibrators with an average power of 2.3 kW which reach vibrating performances of up to 35 m^3/h, according to the technical data sheets of the different models.

Finally, regarding this specific construction process following the HPO solution compared to solutions using pre-stressed concrete beams (VDT, VAR1 and VAR2). The construction process requires the following machinery in general: laying of sheaths and trumpets, stringing of the strings, stressing of the tendon, cutting of the ends and sealing of boxes, and finally, the reinforcement of the foundation.

According to all these phases, we can summarise that the specific machinery needed during the execution of the specialised post-tensioning works are: cable straightening machine, hydraulic jack with hydraulic power unit (hydraulic pump with electric motor) for its operation, hand radial-type cutter and injection pump. In accordance with average characteristics for the execution of post-tensioned concrete in buildings, the following machines (all of them with three-phase current) have been considered based on the documentation provided by various manufacturers Hydraulic Cable Trimmer 0,5″–0,6″ (8 kW), Jack and Hydraulic (10 kW), Continuous Flow Injection Pump 12.5 L/min-8 bar (8 kW) and Radial Type Cutter (2.2 kW).

Applying the corresponding sub-model to calculate of emissions associated with the construction process, we can see how the solution with the lowest volume of emissions corresponds to the solution that was implemented in the actual case study: VDT (Table 8).

Table 8. CO_2 Emissions Calculation: Building Process (E_{PC}).

CONCRETE LAYING	VDT	VAR1	VAR2	HPO
Tower Crane				
Downloads / Transfers	0.095	0.124	0.095	0.666
Execution of works	0.998	1,198	0.998	3.728
Mobile Crane				
Displacement	1.483	1.977	1.977	-
Placement of Premanufactured Beams	1.297	2.076	2.076	-
Concrete Self-Pump				
Displacement	0.016	0.032	0.016	0.032
Execution of works	1.090	1.526	1.090	1.526
Iron Workshop				
Cutting machine	0.038	0.048	0.029	0.125
Bending machine	0.173	0.213	0.133	0.280
Stirrupper	0.008	0.008	0.004	0.033
Concrete Compression				
Concrete Vibrators	0.020	0.029	0.020	0.029
Post-tensioned concrete				
Stretcher	-	-	-	0.169
Jack	-	-	-	0.318
Injection pump	-	-	-	0.213
Cutter	-	-	-	0.028
[T CO_2]	5.219	7.230	6.438	7.145

4.4. Temporary Traffic Diversions

In order to determine the volume of traffic affected during the execution of the works, we took into account the traffic data corresponding to the year in which said works were carried out (2007) based on the data published in the city of Seville's urban traffic site [50], where the route used has an Annual Daily Traffic (ADT) of 12,974 vehicles/day for the route affected by the provisional detours put into place for the duration of the works. Traffic was dissected as follows: motorcycles (4.6%), cars including taxis (90.7%), trucks (1.8%) and buses (2.9%), with different hypotheses being established as to the type of fuel used by each type of vehicle.

The results of the implementation of the corresponding sub-model prove that VAR2 is the solution with the lowest volume of emissions (Table 9), followed very closely by VDT and VAR1, and with the HPO solution standing out negatively as a result of the longer runtime of the works.

Table 9. Calculation of CO_2 Emissions (T): Temporary Traffic Diversions.

Traffic Diversions	VDT	VAR1	VAR2	HPO
Motorbikes	0.228	0.232	0.212	0.374
Cars and Taxis	13.068	13.293	12.166	21.404
Trucks	1.127	1.146	1.049	1.846
Buses	2.263	2.302	2.107	3.707
[T CO_2]	16.686	16.973	15.535	27.330

It is worth noting that in the hypothetical case that the traffic diversion implied a reduction in the usual travel time of the vehicles in comparison to the original route, the runtime of the construction works would have played a fundamental role, and the importance of the solutions would have been reversed. If we had considered a reduced journey length equal to the one actually considered (hypothetically), the HPO solution would be the most efficient regarding the volume of emissions avoided, constituting the best solution compared to the rest.

4.5. Dust, Noise and Vibration Emissions

Firstly, the buildings that make up the immediate proximity ring have been assessed as potential receptors of the combined emissions of dust, noise and vibrations, which will act as a "screen" against the adjacent rings. Based on this assessment, we have first identified the buildings intended for residential use, taking into account the available cadastral data, along with surface area as well as the year of construction. Similarly, and with some consultation tools complementary to those used in the case of residential use, we have proceeded to assess the singular buildings of the first ring of affection, also specifying their address, as well as their main use.

Once an adequate assessment of the buildings that makes up the primary ring of potential impact or affection has been performed, the main variable to be taken into account according to the established hypotheses is the distance between the buildings and the point of the construction works (the source of the dust, noise and vibration emissions). To this end, we have used the catalogue of metadata provided by the Spatial Data Infrastructure (SDI) [51] to determine the distance between the geometric centres of the assessed buildings and the geometric centre of the propped-up foundation under study. Thus, we have considered a trapezoid-type weight distribution, in order for the minimum distance to be weighted with a percentage of effect of 100% and the maximum, with a degree of effect of 50%.

Following this, we determined the energy consumption attributed to air conditioning in each of the buildings based on the data provided by IDAE [38], which establishes the reference values for air conditioning, among others (heating and domestic hot water), which in the case of Seville amounts to 23.40 kW per m^2 per year. For the case in question (Seville), we have taken into account that the energy consumption of air conditioning systems occurs in the summer months and partially in late spring and early autumn. In operational terms, we have considered that this consumption occurs in the six months between May and October. Based on this distribution of consumption during "hot" months, we have established the "affected" demand, i.e., that part of the demand of energy during the period of execution of the works for each of the analysed building solutions.

Having determined the affected energy demand (energy consumption associated with the period of execution of the works) we have proposed a new variable to allow us to determine the increase in energy consumption caused by the need to switch on the air conditioning systems due to having closed the windows to avoid the effect of the aforementioned emissions, a need that would otherwise arise later in the day if it were not for these emissions. In our case, we have established an average daily increase of 4 h a day in the usage of air conditioning systems, and in days with an average use of 10 h, this represents an increase of 40% (the hypothesis raised is that the air conditioning systems are activated at 8:00 in the morning when in conditions of absence of dust, noise and vibrations, it would be activated on average at 12:00 noon, which is when the heat sensation at home and the workplace becomes uncomfortable.

In the case of the regarded areas and their types of activity and occupancy rates (homes, commercial spaces, hotel rooms, classrooms in learning centres and universities, premises in stations, etc.) different hypotheses have been established in accordance with the available data which affect the results obtained from different activity coefficients associated with the particularities of each case.

The only differential variable is the runtime of the building process. In the case of the study, the analysed solutions show different runtimes. However, if we consider the duration of the different hypotheses and the actual start date of the construction works, in every case the time period surpasses the following date: 31 October 2007, which is the deadline at which we have considered that energy consumption takes place, so the percentage of affected demand amounts to 32.61% (which corresponds to a proportion of 60 days, in all hypotheses, out of a total of 184 days corresponding to the six months considered from May to October: the hot months).

Therefore, when applying the proposed sub-model, the same level of emissions has been obtained for all the analysed solutions, as shown in the table below (Table 10).

As a hypothesis, we have obtained the possible result of the application of the sub-model in the case that the entire execution time of the works, for each analysed solution, was carried out within the yearly period affected by the higher demand for air conditioning (the hotter months). In this case, the period is the determining factor, and it can be seen that the solution with the lowest volume of emissions corresponds to the VAR2 solution, which is the solution with the shortest execution period (Table 11).

Table 10. Calculation of CO_2 Emissions: Dust, Noise and Vibrations.

Dust, Noise and Vibrations	VDT	VAR1	VAR2	HPO
Housing Buildings	29.913	29.913	29.913	29.913
Commercial Spaces	4.567	4.567	4.567	4.567
Singular Buildings	24.765	24.765	24.765	24.765
[T CO_2]	59.245	59.245	59.245	59.245

Table 11. Calculation of CO_2 Emissions (T): Dust, Noise and Vibrations. Hypothesis considering the deadline within the time most affected by the demand for Refrigeration.

Dust, Noise and Vibrations	VDT	VAR1	VAR2	HPO
Housing Buildings	38.887	39.884	36.394	63.814
Commercial Spaces	5.937	6.089	5.557	9.743
Singular Buildings	32.194	33.020	30.130	46.692
[T CO_2]	77.018	78.993	72.081	120.249

4.6. Load Test

With regard to the calculations performed, we have taken into account the movements of the trucks to the building sites for the load tests and the movement needed to perform the actual test (static and dynamic). Similarly, the data included in the results report of the loading test and an average speed of 50 km/h were considered for the calculation, in order to obtain an equivalent journey length that is accurately representative. Finally, the fuel consumption associated with the time used by a 75 kW backhoe loader during the loading of the trucks with soil until they reach the required weight for the different load tests has also been considered.

By applying the corresponding sub-model, it should be pointed out that the load test would have been the same for any of the technical building solutions proposed; therefore, the volume of emissions obtained is the same in all cases (Table 12).

Table 12. Calculation of CO_2 emissions: Load Test (E_{PPC}).

LOAD TEST	VDT	VAR1	VAR2	HPO
Transportation	0.816	0.816	0.816	0.816
Transit of Trucks (Load Test)	0.351	0.351	0.351	0.351
Loading of Trucks	0.001	0.001	0.001	0.001
[T CO_2]	1.168	1.168	1.168	1.168

As mentioned, IVMSA is the basis of the ICSS (value added), and this paper does not aim to take a deeper look at the sub-models associated with it. This paper focuses on the sub-models of the variables that are not taken into account in obtaining the ICSS. These are disaggregated models (the results are quantifiable in terms of CO_2 emissions, unlike the ICSS which gives us a level of contribution of the structure or foundation to sustainability, A, B, C, D or E).

5. Results

The obtained results are included in detail in Table A1 of Appendix A, which include the global volume of CO_2 emissions calculated for each of the building solutions considered in the case study, after the application of the sub-model corresponding to each of the non examined variables in the proposed disaggregated model. Table 13 shows its summary (in TCO_2): 88.9 for the implemented solution VDT, 98.092 for the alternative VAR1, 93.963 for the alternative VAR2 and 109.685 for the alternative HPO.

Table 13. Level of CO_2 Emissions. CO_2 total of non examined variables.

Results:	VDT	VAR1	VAR2	HPO
Transportation of Material	5.775	12.730	10.871	13.563
Worker's Commute	0.808	0.746	0.707	1.234
Laying of Concrete	5.219	7.230	6.438	7.145
Temporary Traffic Diversions	16.686	16.973	15.535	27.330
Dust, Noise and Vibration Emissions	59.245	59.245	59.245	59.245
Load Test	1.168	1.168	1.168	1.168
Total CO_2 Emissions (T)	88.900	98.092	93.963	109.685

Indeed, the significance of the research lies in the order of quantitative magnitude of the variables not contemplated in ICSS, not in the result of VDT, VAR1, VAR2 and HPO, hence the analysis of the representativeness of the obtained results. However, the results, according to the hypotheses raised, are the ones published. The discussion of results should emphasise the methodology on the one hand (already described) and the order of magnitude of the modelled aspects on the other hand.

6. Discussion

In view of the overall impact when considering all the non examined variables together, it appears that the actual solution implemented (VDT) has proved to be the most "sustainable", with a reduction in the volume of emissions of 9.4% compared to the solution based on the use of trough-beams of 1.50 m edge with 60 cm slab (VAR1), 5.4% compared to the solution also based on the use of trough-beams but 1.70 m edge with 30 cm slab (VAR2) and a considerable 18.9% in the case of the solution based on the use of post-tensioned concrete (HPO), as we can see in the following graph (Figure 5).

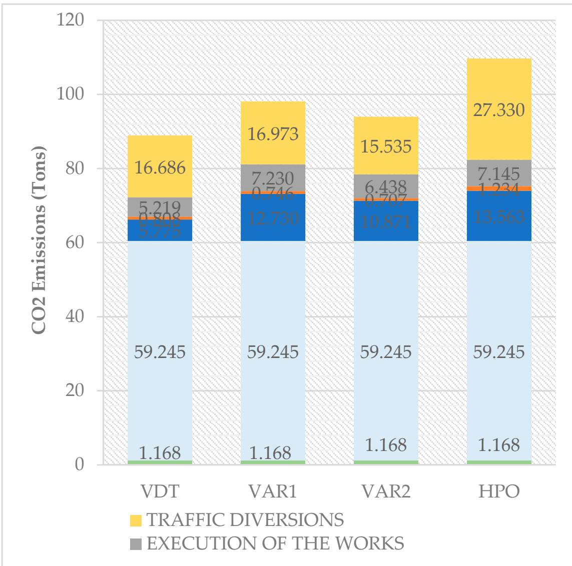


Figure 5. CO_2 Emissions Comparison: non examined variables.

In the case of the most sustainable solution, according to the results obtained (VDT), we can see that 67% of the emissions generated have their origin in the increases in electricity consumption associated with the combined emissions of dust, noise and vibrations, while the emissions derived from traffic diversions put into place in one of the lanes of Ramón y Cajal Avenue represent almost 20%

of the estimated total, with both aspects representing a volume of emissions close to 87% of the total. The rest of the emissions are distributed mainly between those derived from the transportation of material to the construction site (6%) and from the use of the necessary means for the laying of concrete (6%) as well as from the commute of workers and the required load test, in both cases, with percentages of around 1% of the total emissions, as shown in the following figure (Figure 6).

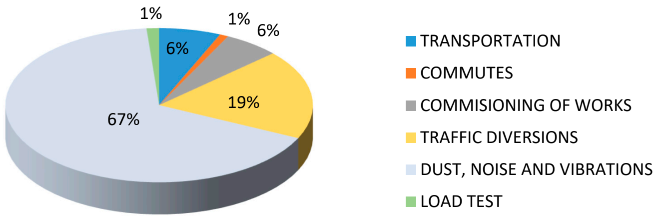


Figure 6. Origin of CO_2 Emissions in non examined variables. EHE-08 (VDT).

Similarly, it should be noted that out of all the variables not examined by EHE-08, the emissions of dust, noise and vibrations is the one that presents the highest uncertainty, unpredictability and difficulty when attempting to extrapolate it to other areas. If this variable where not taken into account, temporary traffic diversions would become the main source of CO_2 emissions (with a percentage of 56%), compared to the transportation of materials (19%) and the laying of concrete (18%), as shown in Figure 7.

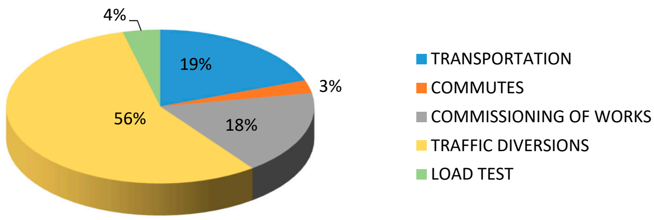


Figure 7. Origin of CO_2 Emissions in non examined variables. EHE-08 (VDT) without taking into account Dust, Noise and Vibration emissions.

In a similar way, temporary traffic diversions may or may not be necessary in construction works carried out in urban environments, as in fact is the case commonly. Regarding the building solution that was implemented in the case study (VDT), if the emissions of dust, noise and vibrations are not taken into account and traffic diversions are not necessary, we can see (as shown in Figure 8) that the main source of CO_2 emissions is the transportation of materials to the work site, with a percentage of 45%, compared to the implementation of the VDT building solution, which in the particular case of said solution, has a percentage of 40%. Similarly, the commute of workers from their places of residence or accommodation represents 6% of the overall emissions, while the load test raises its percentage to 9%, although the special circumstances surrounding its implementation in this type of unique foundation have already been mentioned.

In every work of research, highlighting its potential and its weaknesses becomes necessary. In this sense, regarding the limitations of the research, it is worth noting that they are closely linked to its level of scale (the execution of foundations and building structures, although they could be adapted, depending on the case, to structures and foundations of civil and/or industrial works), as well as to the starting methodology (the EHE Concrete Instruction), given that the CDM-SABSSF methodology focuses on the variables that are not explicitly considered by the aforementioned.

However, the greatest potential of this research is the evaluation of the sustainability levels of structures and foundations at this scale, regardless of other conditioning factors pertaining to the LCA of the building.

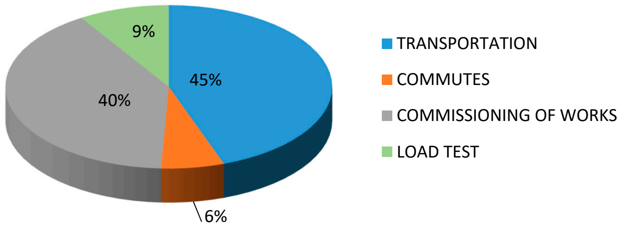


Figure 8. Origin of CO_2 Emissions in non examined variables. EHE-08 (VDT) without taking into account Dust, Noise and Vibration emissions and Temporary Traffic Diversions.

It is worth noting that most building projects are not subject to sustainability requirements (LEED type certification, or similar); however, a large percentage of these projects show relevant modifications at the level of structural and foundation solutions; in many cases, this is due to the technical and/or economic optimisation of the solutions included in the projects and in others to solve geological or geotechnical index problems that have not been taken into account for different reasons.

In both cases, the methodology proposed by the EHE (Concrete Instruction) in Spain, allows us to evaluate the sustainability levels of the different solutions and the proposed methodology (CDM-SABSSF), to take into account the variables that were previously unexamined, and that in certain situations can be differential when determining a building solution's contribution to sustainability at that scale (phase of execution of structures and foundations in projects without specific sustainability requirements).

From the performed analysis, when the proposed methodology is applied to the real case study, the most sustainable solution is the one established by ICSS. But this is a mere coincidence. In fact, in the sub-model with the greatest limitations, the same result is obtained by taking into account the real dates on which the works were carried out. If they had taken place on other (warmer) dates, the results would have been significantly different, taking into account the proportionality with the execution time of each of the solutions analysed. On the other hand, the load test was necessary in all the solutions analysed, but it would not have been necessary in a solution in situ that had not been tested, so that in quantitative terms we have obtained an order of magnitude of its representativeness in the decision-making process.

In conclusion, if certain conditions had changed, the most sustainable solution might have been a different one. In the case study, the choice was made without taking into account any requirements regarding sustainability. That the VDT solution was the most sustainable is a mere coincidence as shown in the research presented here, proving how the sustainability of a building solution can change in relation to the indicators or analytical tools used.

At this scale, this research is unprecedented in relation to certain variables (noise, dust, vibrations, temporary traffic diversions, load test, etc.), so it is not possible to mention a greater number of case studies, as this one is unique. Only a small amount of research has had an impact at this scale, on aspects such as the laying of concrete; but without taking into account, for instance, the transportation of workers to the building site [27]. It is to this very reason that this research owes its importance, to serve as a stepping stone for future cases of a similar kind. The selected case has allowed us to highlight and put into context the sustainability impact that the variables included in the proposed methodology (CDM-SABSSF) may have.

In relation to the sensitivity of the variables taken into account in the proposed methodology, it is worth highlighting:

- The most notable impact pertains to the influence that the generation of dust and noise can have in urban environments, and that in the case of the study, it does not have relative influence as the execution periods of the different alternatives are carried out outside the sensitivity period (according to the actual execution period of the works). This aspect is by far the most qualitatively relevant (potential for CO_2 emissions), and when it comes to the execution of building works in sensitive periods (hot weather) it can be decisive in relation to the decision making process. However, this sub-model is the one with the most limitations, according to the initial hypotheses put forward and the characterisation of the areas of influence, so this must be taken into account when extrapolating and adapting the methodology to other situations, geographical areas and countries.

- On the other hand, it is clear that the execution period is of vital importance in the case of temporary traffic diversions (in favour and against the sustainability of the solution) and yet its applicability is immediate and can be extrapolated to any situation based on the appropriate characterisation of the traffic affected.
- The construction process, and namely the transportation of materials and installation, depends mainly on the technical building solution put into place, and the proposed methodology allows for a quantification of the emissions generated to be obtained from a disaggregated model, so that its adaptation and applicability to other cases is immediate if the solutions are suitably characterised. These aspects are the most influential in the design and execution process and are the ones that are easiest for the agents involved to use to obtain reliable data.
- Finally, the transportation of workers and the execution of the load test are easily applicable to any situation, but the absolute results show a smaller overall impact in the contribution to the sustainability of the analysed building solutions.

7. Conclusions

The application of the methodology described in Annex 13 of EHE-08 to determine the Index of Contribution of the Structure to Sustainability (ICSS, ICES in Spanish), shows us how, in every case, the same level of "sustainability" (an equivalent ICSS index to level C) is obtained, both in the real case study and in the suggested alternatives. To evaluate the contribution of structures to sustainability, using the tools currently available seems like the sensible choice, as they provide the basis for a homogeneous comparison between the different agents involved in the construction process. However, as this research has shown, they must be complemented with other tools based on the disaggregation of the construction process, and the assessing of quantitative indicators (energy and fuel consumption, CO_2 emissions, etc.) so as to establish a suitable comparison in terms of sustainability, mainly in those cases where different solutions obtain similar sustainability rates (which means that a sufficiently representative comparison cannot be established). This is mainly due to the fact that some relevant variables have not been examined and accounted for. Among said variables that are worth noting: the transportation of materials, movement of workers, construction process or implementation, temporary traffic diversions, dust, noise and vibration emissions and the need to carry out a load test.

Based on this scenario, the main goal of this research has been developing a complementary disaggregated model for the evaluation of the sustainability of building solutions in the structure and foundation phase of the construction process (CDM-SABSSF). The reason why it was initially proposed as a complementary model is due to the aforementioned requirement to guarantee a single and homogeneous comparative framework within the reach of all the agents involved in the construction process, i.e., according to this premise, it is necessary to have the existing tools and to complement their use and the decision-making derived from their application with tools that allow us to take into account the variables that have otherwise been left out and unexamined.

On the other hand, based on the results obtained in the case study, and given the complexity of estimating the emissions derived from the overconsumption of energy associated with the emission of dust, noise and vibrations (increased use of air conditioning systems due to having the need to close the windows for longer than would be the case if the construction works had not taken place) as well as the need to carry out studies to contrast and calibrate the hypotheses put forward during the proposal of the corresponding sub-model, we have carried out a representativeness analysis, ignoring the results obtained with respect to the rest of the variables, and this has shown that the highest emission levels correspond to the temporary traffic diversions (varying from 56% in the VDT solution to 44% in the

VAR1 solution) followed by the transportation of materials (with percentages varying from 19% in the VDT solution to 33% in the VAR1 solution). In this analysis, the implementation shows less divergence between the different solutions, with levels of emissions varying from 14% for HPO solution to 19% for VAR2 solution. Finally, the joint percentage in relation to workers' commute and the load test shows some differences, varying between 7% of the VDT solution and 5% in the rest of the solutions analysed.

Similarly, and taking into account the exceptional nature of temporary traffic diversions (which may or may not occur at a given building site), we have performed a similar analysis, without considering the emissions for this aspect (as was done with the emissions derived from dust, noise and vibrations for the reasons already mentioned), and thus reaching important conclusions applicable to most actions at this level. From this analysis we can observe and conclude that, for the case study, the highest level of emissions corresponds to the transportation of materials to the worksite, with percentages of 45% in the case of the real case study (VDT) and percentages between 57% and 59% for the rest of the options considered. With regard to the works related to the laying of concrete, which is the second most important aspect, the percentages vary from 31% for the HPO solution to 40% for the VDT solution, while the combined percentage of emissions corresponding to the movement of workers and the load test vary from 9–10% for the VAR1, VAR2 and HPO solutions to 14% for the VDT solution.

Finally, in order to qualitatively scale the impact of the variables not examined by the currently available methodology and for which a disaggregated model has been developed in this paper, in relation to the level of overall emissions considering the steel and cement manufacturing process (as the main materials of reinforced concrete) we find that these variables can account for between 12% and 14% of the total volume of emissions depending on the particular solution considered in each case.

The results obtained in this research are a firm commitment to sustainability in foundations and building structures, taking into account that the unique cases are an opportunity in the design and execution phase to favour circular economy in all the construction systems and procedures that take place; the data we have obtained in this paper shows how foundation works executed without sustainability criteria could have been done if they had taken these variables into account, without modifying the required structural results and nevertheless contributing to mitigate climate change from the perspective of the inclusion of variables not hitherto examined at this level, with a high margin of action to reduce the consumption of material resources in the construction sector in particular, and in the field of civil engineering in general.

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Appendix A

Table A1. Level of CO_2 Emissions. CO_2 total of non examined variables.

Transportation of Materials					
		VDT	**VAR1**	**VAR2**	**HPO**
	Transportation of Concrete	4.549	6.334	4.491	6.334
	Transportation of beams	1.163	6.286	6.286	0.000
	Transportation of B500S Steel	0.025	0.034	0.017	0.067
	Transportation of Formwork	0.038	0.077	0.077	7.162
	[T CO_2]	5.775	12.730	10.871	13.563
Workers' commute					
		VDT	**VAR1**	**VAR2**	**HPO**
	Petrol vehicles	0.385	0.355	0.337	0.296
	Diesel Vehicles	0.423	0.391	0.370	0.938
	[T CO_2]	0.808	0.746	0.707	1.234
Concrete Laying					
		VDT	**VAR1**	**VAR2**	**HPO**
	Tower Crane				
	Downloads / Transfers	0.095	0.124	0.095	0.666
	Use	0.998	1.198	0.998	3.728
	Mobile Crane				
	Transportation	1.483	1.977	1.977	0.000
	Placement of Prefabricated Beams	1.297	2.076	2.076	0.000
	Concrete Pump				
	Transportation	0.016	0.032	0.016	0.032
	Use	1.090	1.526	1.090	1.526
	Iron Workshop				
	Cutting machine	0.038	0.048	0.029	0.125
	Bending machine	0.173	0.213	0.133	0.280
	Stirrupper	0.008	0.008	0.004	0.033
	Concrete Compression				
	Concrete Vibrator	0.020	0.029	0.020	0.029
	Post-tensioned concrete				
	Stretcher	0.000	0.000	0.000	0.169
	Jack	0.000	0.000	0.000	0.318
	Injection Pump	0.000	0.000	0.000	0.213
	Cutter	0.000	0.000	0.000	0.028
	[T CO_2]	5.219	7.230	6.438	7.145
Traffic Diversions					
			VDT	**VAR1**	**VAR2**
	Motorbike	0.228	0.232	0.212	0.374
	Cars & Taxis	13.068	13.293	12.166	21.404
	Trucks	1.127	1.146	1.049	1.846
	Buses	2.263	2.302	2.107	3.707
	[T CO_2]	16.686	16.973	15.535	27.330
Dust, Noise and Vibrations					
		VDT	**VAR1**	**VAR2**	**HPO**
	Housing Buildings	29.913	29.913	29.913	29.913
	Commercial Spaces	4.567	4.567	4.567	4.567
	Singular Buildings	24.765	24.765	24.765	24.765
	[T CO_2]	59.245	59.245	59.245	59.245
Load Test					
		VDT	**VAR1**	**VAR2**	**HPO**
	Transportation of Material	0.816	0.816	0.816	0.816
	Transit of Trucks (Load Test)	0.351	0.351	0.351	0.351
	Loading of Trucks	0.001	0.001	0.001	0.001
	[T CO_2]	1.168	1.168	1.168	1.168
TOTAL	[T CO_2]	88.900	98.092	93.963	109.685

References

1. Fuertes, A.; Casals, M.; Gangolells, M.; Forcada, N.; Macarulla, M.; Roca, X. An Environmental Impact Causal Model for improving the environmental performance of construction processes. *J. Clean. Prod.* **2013**, *52*, 425–437. [CrossRef]
2. Badi, S.; Murtagh, N. Green supply chain management in construction: A systematic literature review and future research agenda. *J. Clean. Prod.* **2019**, *223*, 312–322. [CrossRef]
3. Ahmad, M.; Zhao, Z.-Y.; Li, H. Revealing stylized empirical interactions among construction sector, urbanization, energy consumption, economic growth and CO_2 emissions in China. *Sci. Total Environ.* **2019**, *657*, 1085–1098. [CrossRef] [PubMed]
4. Zutshi, A.; Creed, A. An international review of environmental initiatives in the construction sector. *J. Clean. Prod.* **2015**, *98*, 92–106. [CrossRef]
5. Jiménez Herrera, L.M. *Desarrollo Sostenible—Transición Hacia la Coevolución Global*; Ediciones Pirámide: Madrid, Spain, 2000.
6. Fernández Latorre, F. *Indicadores de Sostenibilidad y Medioambiente: Métodos y Escala*; Consejería de Medio Ambiente: Junta de Andalucía, Sevilla, Spain, 2011. Available online: http://www.juntadeandalucia.es/medioambiente/web/Bloques_Tematicos/Sostenibilidad/Estrategia_andaluza_desarrollo_sostenible/libro_indicadores_sostenibilidad/3_cap_1_3.pdf (accessed on 23 June 2020).
7. Bell, S.; Morse, S. Sustainability Indicators Past and Present: What Next? *Sustainability* **2018**, *10*, 1688. [CrossRef]
8. Solís-Guzmán, J.; Rivero-Camacho, C.; Alba-Rodríguez, D.; Martínez-Rocamora, A. Carbon Footprint Estimation Tool for Residential Buildings for Non-Specialized Users: OERCO2 Project. *Sustainability* **2018**, *10*, 1359. [CrossRef]
9. Mercader, P. Cuantificación de los Recursos Consumidos y Emisiones de CO_2 Producidas en las Construcciones de Andalucía y sus Implicaciones en el Protocolo de Kioto. Ph.D. Thesis, Universidad de Sevilla, Seville, Spain, 2011. Available online: http://fondosdigitales.us.es/tesis/tesis/1256/cuantificacion-de-los-recursos-consumidos-y-emisiones-de-co2-producidas-en-las-construcciones-de-andalucia-y-sus-implicaciones-en-el-protocolo-de-kioto/ (accessed on 23 June 2020).
10. Sánchez, O.J.; Cardona, C.A. Análisis de ciclo de vida. *Rev. Univ. EAFIT* **2007**, *43*, 59–79.
11. Cabeza, L.F.; Rincón, L.; Vilariño, V.; Pérez, G.; Castell, A. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renew. Sustain. Energy Rev.* **2014**, *29*, 394–416. [CrossRef]
12. Pilger, J.D.; Machado, Ê.L.; de Assis Lawisch-Rodriguez, A.; Zappe, A.L.; Rodriguez-Lopez, D.A. Environmental impacts and cost overrun derived from adjustments of a road construction project setting. *J. Clean. Prod.* **2020**, *256*, 120731. [CrossRef]
13. ISO. *Environmental Management: Life Cycle Assessment; Principles and Framework*; ISO: Geneva, Switzerland, 2006.
14. Simpson, B.; Tatsuoka, F. Geotechnics: The next 60 years. *Géotechnique* **2008**, *58*, 357–368. [CrossRef]
15. Brandl, H. Energy foundations and other thermo-active ground structures. *Géotechnique* **2006**, *56*, 81–122. [CrossRef]
16. DeJong, J.T.; Soga, K.; Kavazanjian, E.; Burns, S.; Van Paassen, L.A.; Al Qabany, A.; Chen, C.Y. Biogeochemical processes and geotechnical applications: Progress, opportunities and challenges. *Géotechnique* **2013**, *63*, 287–301. [CrossRef]
17. Camporeale, P.; Mercader-Moyano, P. Towards nearly Zero Energy Buildings: Shape optimization of typical housing typologies in Ibero-American temperate climate cities from a holistic perspective. *Sol. Energy* **2019**, *193*, 738–765. [CrossRef]
18. Shillaber, C.M.; Mitchell, J.K.; Dove, J.E. Energy and Carbon Assessment of Ground Improvement Works. I: Definitions and Background. *J. Geotech. Geoenviron. Eng.* **2016**, *142*. [CrossRef]
19. Shilaber, C.M.; Mitchell, J.K.; Dove, J.E. Energy and Carbon Assessment of Ground Improvement Works. II: Working Model and Example. *J. Geotech. Geoenviron. Eng.* **2016**, *142*. [CrossRef]
20. Ministerio de la Presidencia. REAL DECRETO 1247/2008, de 18 de Julio, por el que se Aprueba la Instrucción de Hormigón Estructural (EHE-08). *Boletín Oficial Estado* **2008**. Available online: http://www.fomento.es/nr/rdonlyres/e20dffb7-fd75-4803-8ca4-025064bb1c40/68186/1820103_2008.pdf (accessed on 23 June 2020).

21. Suárez, M.; Gómez-Baggethun, E.; Benayas, J.; Tilbury, D. Towards an Urban Resilience Index: A Case Study in 50 Spanish Cities. *Sustainability* **2016**, *8*, 774. [CrossRef]
22. Ariaratnam, S.T.; Piratla, K.; Cohen, A.; Olson, M. Quantification of Sustainability Index for Underground Utility Infrastructure Projects. *J. Constr. Eng. Manag.* **2013**, *139*, A4013002. [CrossRef]
23. Cianciarullo, M.I. Green construction—Reduction in environmental impact through alternative pipeline water crossing installation. *J. Clean. Prod.* **2019**, *223*, 1042–1049. [CrossRef]
24. Celauro, C.; Corriere, F.; Guerrieri, M.; Lo Casto, B.; Rizzo, A. Environmental analysis of different construction techniques and maintenance activities for a typical local road. *J. Clean. Prod.* **2017**, *142*, 3482–3489. [CrossRef]
25. Yang, S.-H.; Liu, J.Y.H.; Tran, N.H. Multi-Criteria Life Cycle Approach to Develop Weighting of Sustainability Indicators for Pavement. *Sustainability* **2018**, *10*, 2325. [CrossRef]
26. Paschalidou, A.K.; Kassomenos, P.A.; Kelessis, A. Tracking the association between metro-railway construction works and PM levels in an urban Mediterranean environment. *Sci. Total Environ.* **2016**, *568*, 1326–1332. [CrossRef] [PubMed]
27. Mel Fraga, J.; Del Caño Gochi, A.; De la Cruz López, M.P. Sustainability in the Preparation, Transport and Casting of the Concrete in Spain: Analysis of Energy Consumption and CO_2 Emissions. In Proceedings of the 18th International Congress on Project Management and Engineering, Alcañiz, Teruel, Spain, 16–18 July 2014. Available online: http://www.aeipro.com/files/congresos/2014alcaniz/CIDIP2014_0508_0520.4196.pdf (accessed on 23 June 2020).
28. Luo, W.; Sandanayake, M.; Zhang, G. Direct and indirect carbon emissions in foundation construction—Two case studies of driven precast and Cast-In-Situ piles. *J. Clean. Prod.* **2019**, *211*, 1517–1526. [CrossRef]
29. Li, L.; Li, Z.; Li, X.; Zhang, S.; Luo, X. A new framework of industrialized construction in China: Towards on-site industrialization. *J. Clean. Prod.* **2020**, *244*, 118469. [CrossRef]
30. Mercader Moyano, P.; Roldán Porras, J.; Ramirez de Arellano Agudo, A. Sustainability Assessment in Singular Structures, Foundations and Structural Rehabilitation in Spanish Legislation. *Open Constr. Build. Technol. J.* **2017**, *11* (Suppl. 1), 95–109. [CrossRef]
31. Hammad, A.W.A.; Akbarnezhad, A.; Wu, P.; Wang, X.; Haddad, A. Building information modelling-based framework to contrast conventional and modular construction methods through selected sustainability factors. *J. Clean. Prod.* **2019**, *228*, 1264–1281. [CrossRef]
32. Sandanayake, M.; Zhang, G.; Setunge, S. Environmental emissions at foundation construction stage of buildings—Two case studies. *Build. Environ.* **2016**, *95*, 189–198. [CrossRef]
33. Martínez, S.; González, C.; Hospitaler, A.; Albero, V. Sustainability Assessment of Constructive Solutions for Urban Spain: A Multi-Objective Combinatorial Optimization Problem. *Sustainability* **2019**, *11*, 839. [CrossRef]
34. FEMA. *Rapid Visual Screening of Buildings for Potencial Seismics Hazards, A Hand Book*, 2nd ed.; Federal Emergency Management Agency: Washington, DC, USA, 2002.
35. Zhang, H.; Xing, F.; Liu, J. Rehabilitation decision-making for buildings in the Wenchuan area. *Earthq. Constr. Manag. Econ.* **2011**, *29*, 569–578. [CrossRef]
36. Ewing, R.C. Foundation repairs due to expansive soils: Eudora Welty House, Jackson, Mississippi. *J. Perform. Constr. Facil.* **2011**, *25*, 50–55. [CrossRef]
37. Wilder, D.; Smith, G.C.G.; Gómez, J. Issues in design and evaluation of Compaction Grouting for foundation repair. In *Innovations in Grouting and Soil Improvement*; ASCE: Reston, VA, USA, 2005; pp. 1–12.
38. Seksinsky, E.J.; Qubain, B.S. An underpinning solution to a persistent foundation settlement problem. In *Soil Improvement for Big Digs*; ASCE: Reston, VA, USA, 1998; pp. 202–213.
39. Lutenegger, A.J.; Kemper, J.H. Preservation of historic structures using Screw-Pile foundations. In Proceedings of the 6th International Conference on Structural Analysis of Historic Construction, SAHCo8, Bath, UK, 2–4 July 2008; pp. 1079–1086. [CrossRef]
40. Da Casa, F.; Echevarría, E.; Celis, F. El movimiento en la ejecución de recalces con inyección armada. Análisis de tres casos con movimientos previos. *Inf. Construcción* **2012**, *64*, 507–518. [CrossRef]
41. Pineda, P.; García-Martínez, A.; Castizo-Morales, D. Environmental and structural analysis of cement-based vs. natural material-based grouting mortars. Results from the assessment of strengthening Works. *Constr. Build. Mater.* **2017**, *138*, 528–547. [CrossRef]
42. Ferreira Sánchez, A.; Alba Rodríguez, M.D.; de Ramirez Arellano Agudo, A.; Marrero, M. Recalce en condiciones de emergencia: 40 viviendas cercanas al río Guadalquivir, España. *Inf. Construcción* **2016**, *68*, 133. [CrossRef]

43. Oficina Española de Cambio Climático (OECC); Secretaría de Estado de Medio Ambiente del Ministerio de Agricultura; Alimentación y Medio Ambiente de España. *Guía Para el Cálculo de la Huella de Carbono y Para la Elaboración de un Plan de Mejora de una Organización*; OECC: Madrid, Spain, 2016. Available online: http://www.mapama.gob.es/es/cambio-climatico/temas/mitigacion-politicas-y-medidas/guia_huella_carbono_tcm7-379901.pdf (accessed on 23 June 2020).
44. Oficina Española de Cambio Climático (OECC); Secretaría de Estado de Medio Ambiente del Ministerio de Agricultura; Alimentación y Medio Ambiente de España. *Factores de Emisión. Registro de Huella de Carbono, Compensación y Proyectos de Absorción de Dióxido de Carbono*; OECC: Madrid, Spain, 2017. Available online: http://www.mapama.gob.es/es/cambio-climatico/temas/mitigacion-politicas-y-medidas/factores_emision_tcm7-359395.pdf (accessed on 23 June 2020).
45. De Fomento, M.; Consulting in Transportation and Logistics (SPIM). Resumen Ejecutivo. In *Ministry of Development: Study of the Costs of Goods Transportation by Road*; Ministry of Development, Government of Spain: Madrid, Spain, 2008. Available online: https://www.fomento.gob.es/NR/rdonlyres/D12A4405-3DE8-4D87-8F06-8CED0E11DD3E/40278/EstudioCostesMercanciasCarreteraoctubre2008.pdf (accessed on 23 June 2020).
46. Asociación de Empresas Constructoras y Concesionarias de Infraestructuras (SEOPAN). *Manual de Costes de Maquinaria de Construcción*; SEOPAN: Madrid, Spain, 2008.
47. Instituto para la Diversificación y Ahorro de la Energía (IDAE). Escala de la Calificación Energética. Edificios de Nueva Construcción. Madrid, Mayo de 2009. Available online: http://www.idae.es/uploads/documentos/documentos_CALENER_07_Escala_Calif_Energetica_A2009_A_5c0316ea.pdf (accessed on 23 June 2020).
48. Sociedad Española de Bombas de Hormigón (SEBHSA). Ficha Técnica Camión con Bomba Para Hormigón 42 m. BC-3907, BC-4147. PL-42/125-5X. (Spanish Society of Concrete Pumps- SEBHSA Technical Specifications for 42 m. BC-3907, BC-4147 and PL-42/125-5X Concrete Pump Trucks). Available online: http://www.sebhsa.com/_data/es/pl-42-125-5x-14.pdf (accessed on 23 June 2020).
49. ALBA-MACREL GROUP, S.L. Maquinas de Ferralla: Cortadora o Cizalla C32L-2,6 kW; Dobladora D36L-3,6 kW; Estribadora D24L-1,1 kW. (Iron Cutting Machines, Bending Machines, ALBA-MACREL GROUP). Available online: http://alba.es/productos/maquinas-de-ferralla (accessed on 23 June 2020).
50. De Sevilla, A. Centro de Gestión de la Movilidad. Delegación de Seguridad, Movilidad y Fiestas Mayores. Portal Tráfico Urbano. Intensidad Media Diaria: Seville, Spain. 2007. Available online: http://trafico.sevilla.org/pdf/ResumenIMD2007.pdf (accessed on 23 June 2020).
51. Infraestructura de Datos Espaciales (IDE). GeoPortal. (Spatial Data Infrastructure (SDI). GeoPortal). Available online: http://sig.urbanismosevilla.org/visorgis/geosevilla.aspx?Layers=IDES&Selected=01&xtheme=brown_12 (accessed on 23 June 2020).