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Characterising Embodied Energy in Construction Activities Using Energy Inventory Life Cycle Assessment Method

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Abstract: Energy consumption of buildings accounts for almost a third of total energy use worldwide, leading to greater efforts in the industry and academia to reduce energy consumption in the built environment. This paper proposes an inventory method integrated within a Life Cycle Analysis (LCA) framework to characterise the energy consumption in the building phase of construction projects early in the construction design process. The proposed approach relies on Data Quality Indicators (DQI) and a Pedigree Matrix to quantify the building's Direct Component of Initial Embodied Energy (DCIEE). In addition, a real case study involving various construction technologies representative of contemporary practice is adopted for validation purposes. Results indicate that the DCIEE of the case study building is 0.481 GJ/m^2, which is slightly higher than that of other studies in the literature that report energy consumption per m^2 of the construction project, mostly due to material transportation being a major contributor in the case study analysed.

Keywords: energy in buildings; life cycle assessment; inventory method; pedigree matrix; direct component of initial incorporated energy

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1. Introduction

The United Nations (UN) Environmental Program pointed out that the construction sector generates between 5% and 10% of jobs at the national level while accounting for 5% to 15% of worldwide GDP [1]. However, the industry is also known for its environmental breaches; the construction industry consumes high rates of energy [2], with buildings accounting for more than 40% of energy consumption and between 30% and 50% of greenhouse gas (GHGs) emissions [3]. In the European Union (EU), construction activities contribute around 40% of total energy consumption and 40% of all manufacturing waste [4]. Energy consumption takes place at all stages of the life cycle of buildings, from the extraction of raw materials to the use of machinery and transportation of building materials and later to the construction, operation, and end-of-life phases of construction projects [5].

Within the context of building construction, Life Cycle Assessment (LCA) is a method that estimates the environmental impacts of the construction process over the full life span of a project, starting from the extraction and production of raw materials process, and ending with the end-of-life approach involved [6]. Studies have focused on proposing an LCA modeling approach for energy matrix scenarios in construction [7] and evaluating the influence of alternative energy routes on the whole energy matrix based on LCA indicators [8]. Others conducted a comparative LCA of industrial objects based on the Data Quality Indicators (DQI) and Pedigree Matrix [9]. DQI is a method that has been designed to evaluate the probability distributions descriptively and used for stochastic modeling of input data in LCA methodology [10]. The Pedigree Matrix is used to evaluate the quality of data sources [11]. A common approach adopted in the literature to promote energy consumption efficiency in buildings is based on using an energy matrix to describe the primary energy sources within a system [12]. The energy matrix is applied to evaluate the environmental impacts of production activities in the construction sector, such as the consumption of non-renewable resources and the generation of GHGs emissions [12]. Studies have focused on the energy consumption in buildings during the operation phase within the life cycle of buildings [13,14]. However, there has been les focus on the construction phase within the life cycle of a building, even though it is known to be an energy-intensive phase that contributes to around 4% of total energy use over the entire lifespan of construction projects [15]. The on-site energy consumption and the production process of building materials are major contributors to both direct and indirect GHGs emissions [16].

The remainder of this paper is organised as follows. In the next section, a literature review is conducted to demonstrate and summarise works performed in the area of energy efficiency in buildings. Later, the methodology adopted to structure the inventory for evaluating DCIEE is presented. Finally, the method is applied to a case study in Brazil, a country known for its high-energy consumption rates in the building sector, to validate the proposed inventory database before discussing the output results of this work in Section 5.

2. Literature Review

Energy consumption values related to the construction industry and the life cycle of buildings are generally high [17,18]. The relationship between energy consumption and GHGs emission in the construction industry was examined [19,20], while various papers analysed the different approaches of LCA adopted in the construction industry [21,22]. Other researchers classified the energy used to produce, transport, and install the elements in buildings [23,24] and presented the importance of life cycle phases in reducing the total life cycle energy in buildings [25,26]. Others analysed the initial incorporated energy in construction projects [27]. Several expressions are used in the literature to characterise the denomination of energy components over the entire life cycle phases of buildings, as presented in Table 1.

Table 1. The denomination of energy components by different authors.

<table>
<tr><th rowspan="2">Source</th><th colspan="5">Life Cycle Phases</th></tr>
<tr><th>Manufacturing Phase</th><th>Construction Phase</th><th>Operation Phase</th><th>Maintenance Phase</th><th>End-of-Life Phase</th></tr>
<tr><td>[28]</td><td colspan="2">Production Energy</td><td>Operation Energy</td><td>Recurrent Embodied Energy</td><td>Demolition Energy</td></tr>
<tr><td rowspan="2">[23]</td><td colspan="2">Initial Embodied Energy</td><td rowspan="2">-</td><td rowspan="2">-</td><td rowspan="2">-</td></tr>
<tr><td>indirect component</td><td>direct component</td></tr>
<tr><td rowspan="2">[29]</td><td colspan="2">Embodied Energy</td><td rowspan="2">Operating Energy</td><td colspan="2">Embodied Energy</td></tr>
<tr><td>indirect component</td><td>direct component</td><td>Recurrent Energy</td><td>Demolition Energy</td></tr>
<tr><td rowspan="2">[30]</td><td colspan="2">Initial Embodied Energy</td><td rowspan="2">Operating Energy</td><td rowspan="2">Recurrent Embodied Energy</td><td rowspan="2">Demolition Energy</td></tr>
<tr><td>indirect component</td><td>direct component</td></tr>
<tr><td>[31]</td><td colspan="2">Embodied Energy</td><td>Operating Energy</td><td colspan="2">Embodied Energy</td></tr>
</table>

The environmental sustainability of the construction sector, via emission and energy reductions, is highly relevant for two reasons: the first concerns the reduction of harmful effects related to the consumption of physical and energy resources and the generation of waste and emissions [32]. It also helps to address the challenge of how to overcome the enormous lack of infrastructure and housing [26], which constitute a social demand typical of a developing country, without compromising resources and environmental quality.

Anderson et al. pointed out that buildings and transportation activities in construction processes account for 62% of final energy consumption and 55% of total GHGs [31]. This comes back to the fact that much of the energy is generated using fossil fuels, resulting in large amounts of CO2 [33]. According to the International Energy Agency, there are objectives for an energy policy of any country: security of supply, environmental protection, and support for economic growth [34]. The primary effort to achieve such objectives should be the investment in energy efficiency and environmental sustainable processes [35,36]. However, energy consumption has dramatically increased in Brazil in the last decades, and the tendency is for it to increase in the future [37]. Although the Brazilian energy source has a cleaner feature than other countries, where 48% of it is based on renewable resources, it is necessary to improve energy efficiency in the construction sector for environmental and economic reasons [33].

Reliability of LCA

It is important to note that the reliability of the LCA method depends mainly on the quality of the inventory of the database adopted. As a result, it is essential to assess the quality of the data in the inventory process, a step which is emphasised in this study, to ensure that LCA outputs are well interpreted and communicated [38]. Singh et al. [39] quantified the embodied energy and carbon footprint of pervious concrete pavements. The authors applied a comparative LCA to deduce the benefits of pervious concrete pavement over Portland cement concrete pavement for different mixing procedures. Guidetti e Ferrara [40] proposed a comprehensive approach to evaluate the consumption of embodied energy based on retroactive and prospective perspectives in terms of life-cycle energy analysis of an existing building. Chen and Lee [41] provided an effective way to identify good quality data through the definition of reference rules using DQI and pedigree matrix. Zhang et al. [42] used DQI and pedigree matrix to assess the level of uncertainty in the LCA of building CO_2 emissions. Yu et al. [43] proposed a methodology to build a probability density function for energy intensity coefficient of pavement materials using three weighted methods, namely DQI, coefficient of variation and analytical hierarchy process. Furthermore, Wang and Chen [44] presented a hybrid stochastic method to develop the uncertainty estimate in LCA with data limitations, using DQI and pedigree matrix. The authors declared that such a study could be used as a valuable tool to evaluate deterministic results of whole-building embodied energy when uncertain information is present. Yu et al. [45] estimated the novelty of this work lies in proposing an accessible approach to assess the embodied energy levels concerning the total energy life cycle in a building, while ensuring valid results when uncertain pdata are present. This will be done via integrating LCA with DQI and the Pedigree Matrix. Data on the following set of activities are collected and validated to evaluate the embodied energy during construction phases in buildings: (i) transportation of materials from the manufacturer to the construction site; (ii) the transportation of labourers; (iii) construction activities taking place on the construction site; and (iv) the transportation of waste, as summarised in Figure 1.

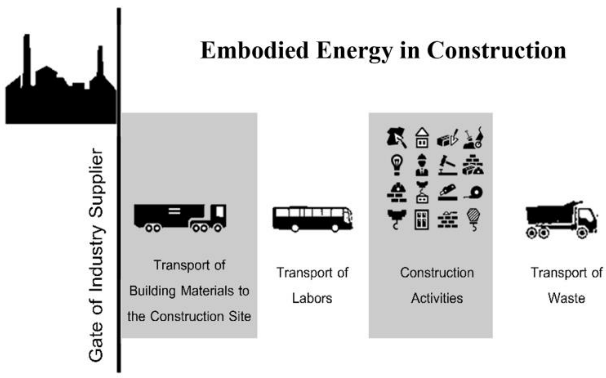

Figure 1. Main components of embodied energy in construction activities.

As seen by the reviewed literature, there is an obvious lack of a systematic procedure that evaluates the energy performance in the construction industry with reliance on the inventory method for LCA, taking into consideration the production activities and uncertain data during the construction phase of buildings.

3. Materials and Methods

Applying LCA in the construction sector requires considering the entire lifespan of buildings to develop and expand frameworks, evaluate the environmental impacts, and assess the quality of data [46]. The LCA method consists of four basic steps: defining the goal and scope (i.e., system boundary, functional equivalent, and scope of the work), life cycle inventory, life cycle impact assessment, and interpretations [47]. The system boundary of this study focuses on the construction of the inventory method based on the LCA method, which models the "inputs" and "outputs" of data through a flow diagram [48] and provides a better understanding of the environmental evaluation in a construction project [49]. In this study, the inventory stage of an LCA analysis is emphasised, focusing on the evaluation of secondary energy inputs of different life cycle phases. The functional equivalent of this work is defined as one square meter (1 m^2) of a constructed area. The results are expressed in units (GJ/m^2) or (GJ/m^2. year) to facilitate a comparison with other studies or phases of the already published research. The DCIEE covers the activities developed, starting from the project's gate to the delivery of the built work. In these terms, the sub-processes of these activities and the related source of energy consumption are summarised in Table 2.

Table 2. Sub-processes, activities, and related energy that make up the system boundary.

Sub-Process	Symbol	Activity	Source of Energy
Transportation of construction materials from the manufacturer to the construction site	E_T	Transport of materials and components from the origin to the construction site	Oil derivative
Transportation of Labour	E_{TL}	Transport of labourers from/to the construction site	Oil derivative
Construction Activities on the Construction Site	E_{TCS}	Vertical and horizontal transport of materials, losses, components, and people at the construction site	Electricity and Oil derivative
	E_P	Production activities, in general, with the use of the equipment	Electricity and Oil derivative
	E_L	Lighting at the construction site	Electricity
Transport of Waste due to Damages and Losses (during the construction phase of buildings)	E_{DL}	Transportation of components and materials from the site to the next destination	Oil derivative

3.1. DCIEE Evaluation

Quantitative data is initially characterised depending on the source of the data. A cost rate database is then integrated with each building component, and a project schedule is finally integrated. Interviews are conducted to supplement the data collection process by filling up data gaps. Then, an extraction of quantities of materials for each project component is performed. The calculation of DCIEE is as given in Equation (1). It is the sum of the total energy consumption during the sub-process activities presented in Table 2.

$$E_{DCIEE} = E_T + E_{TL} + E_{TCS} + E_P + E_L + E_{DL}, \quad (1)$$

where

$\boldsymbol{E_{DCIEE}}$: Represents the direct component of the initial embodied energy (GJ);
E_T: Represents the energy consumption associated with the transport of construction materials and components from the origin to the construction site (GJ);
E_{TL}: Represents the energy consumption associated with the transport of labourers from/to the construction site (GJ);
E_{TCS}: Represents the energy consumption associated with the vertical and horizontal transport of materials, components, and people at the construction site;
E_P: Represents the energy consumption associated with the construction activities in general, as a result of the use of equipment (GJ);
E_L: Represents the energy consumption associated with the lighting at the construction site (GJ);
E_{DL}: Represents the energy consumption associated with the transportation of components and materials from the site to the next destination (GJ).

It is important to note that the DCIEE in this work will be carried out through a case study to validate the database inventory. The sections below will outline the individual components of Equation (1).

3.2. Sub-Processes of the Transportation

This step can be divided into three main activities of transportation, namely the transportation of construction materials from the industry to the construction site (E_T), the transportation of the labourers from and to the construction site (E_{TL}), and transportation of damages and losses produced during the construction phase of buildings from the construction site to the final disposal (E_{DL}).

3.2.1. Transportation of Construction Materials from the Manufacturer to the Construction Site (E_T)

The source of the construction materials and components utilised on a construction site depends on factors such as the size of the construction project, the type of building component under analysis, and even the location of the construction site. The transportation modality considered in this research is road transportation, which is the most used transport modality in Brazil to transport construction materials [50]. Data updated by the National Energy Balance in Brazil considers that each 1 m^3 of diesel oil is equivalent to 35.5 GJ [51]. However, in this study, several vehicle types are considered [52], while accounting for the empty return and the non-use of the total freight capacity of the vehicle. Some studies consider the empty return of the vehicles by adding 43–50% [53,54] to the total calculations of the transportation of construction materials from the manufacturer to the construction site. In this research, an addition of 45% (i.e., coefficient of inactivity of 1.45 will be used) is adopted. The calculation of the energy consumed in the transportation of construction materials and components from the origin to the construction site is defined in Equation (2).

$$E_T = E_{T1} + E_{T2} + \ldots + E_{Tn}, \quad (2)$$

where

E_T: Represents the energy consumption associated with the transport of construction materials and components from the origin to the construction site (MJ);
E_{T1}, E_{T2}, E_{Tn}: Represent the energy consumption associated with each of the different types of materials and components (MJ).

The energy consumed with the transport of each component is defined in two ways, depending on the location of the source of construction material, as shown in Equations (3) and (4) which represent the calculation of this factor for inter-municipal displacement and metropolitan displacement, respectively.

$$E_{Tn} = (d_M \cdot m_n \cdot C_i) \cdot c_o, \quad (3)$$

where

d_M: Represents the distance between the construction site and the factory (km);
m_n: Represents the mass of the component under analysis (t);
C_i: Represents the parameter of energy consumption for inter-municipal or inter-state displacement (0.878 MJ/t. km);
c_o: Represents the inactivity coefficient.

$$E_{Tn} = (d_M \cdot m_n \cdot C_m) \cdot c_o, \quad (4)$$

where

d_M: Represents the distance between the construction site and the factory (km);
m_n: Represents the mass of the component under analysis (t);
C_m: Represents the parameter of energy consumption for metropolitan displacement (1071 MJ/t. km);
c_o: Represents the inactivity coefficient.

3.2.2. Transportation of Labourers (E_{TL})

The energy consumption at this analysis level depends on the type of transportation mode used. Data from the Mobility Information System of the National Association of Public Transport show that these values are 0.14 L/km for the car, 0.04 L/km for the motorcycle, and 0.39 L/km for the bus [55]. Each one (m^3) of diesel fuel equals 35.50 GJ, each one (m^3) of automotive gasoline equals 32.24 GJ, and the average energy consumption of the three types of transportation is 4.536 MJ/km for cars, 1.2636 MJ/km for the motorcycles, and 13.84 MJ/km for the buses [51]. At this level of the analysis, an occupancy rate is indicated based on the location of the projects as follows: 0.2 is applied for car transport, 0.06 is applied for motorcycle transport, and 0.74 is applied for public transport. The weighted average consumption parameter is defined according to Equation (5), which shows that the mean consumption parameter defined is 0.575 MJ/km.

$$C_{MTP} = 0.2E_{MTC} + 0.06C_{MTM} + 0.74C_{MTB}, \quad (5)$$

where

C_{MTP}: Represents the average unit consumption with the automotive transport (MJ/km);
C_{MTC}: Represents the average unit consumption with the transportation by car (1361 MJ/km);
C_{MTM} Represents the average unit consumption with the transportation by motorcycle (1289 MJ/km);
C_{MTB} Represents the average unit consumption with the transportation by public transport (0.307 MJ/km).

Calculating the energy consumed during the transportation of labourers requires considering the weekly workload distributed from Monday to Friday within 44 working hours [56]. Statistical data on average distance and transportation in the metropolitan regions of Brazil can be traced back to the last household survey of transport conducted in 2000 [57]. The results show that for every 44 h of work, there are ten displacements that take place: five in the residence–work direction and five in the work–residence direction. The total number of trips is calculated via Equation (6).

$$N_V = (H_T/44h) * 10, \quad (6)$$

where

N_V: Represents the total number of trips made by the workers;
H_T: Represents the total number of hours used to carry out the activities of the construction site (h);
$44h$: Represents the value of the weekly work accomplished in 5 working days according to the Weekly Work Hours (h);
10: Represents the number of weekly trips.

Finally, the calculation of the amount of energy consumed with the transportation of labour is defined in Equation (7).

$$E_{TL} = N_V \cdot d_M \cdot C_{MTP}, \quad (7)$$

where

E_{TL}: Represents the energy consumption with the transport of labourers from/to the construction site (MJ);
N_V: Represents the total number of trips made by the workforce of the enterprise;
d_M: Represents the average distance traveled in the trips (km);
C_{MTP}: Represents the average unit consumption with the automotive transport (MJ/km).

3.2.3. Transportation of Waste (E_{DL})

Characterising the energy expenditure with these activities requires obtaining the following information: the quantity of discarded materials and components, the place of waste disposal for the definition of transport distances, and the energy consumption related to the loaded vehicle. Thus, the energy consumption is related to transporting damages and losses of construction materials, meaning the transportation of construction and demolition waste that can be characterised by Equation (8).

$$E_{DL} = (d_D \cdot m_D \cdot C_m) \cdot c_o, \quad (8)$$

where

E_{DL}: Represents the energy consumption with the transportation of components and materials from the site to the next destination (MJ);
d_D: Represents the distance between the construction site and the disposal site (km);
m_D: Represents the mass to be discarded (t);
C_m: Represents the parameter of energy consumption for metropolitan displacement (1071 MJ/t. km);
c_o: Represents the inactivity coefficient of loss.

The distance of the transportation of waste is adopted based on the standards used by the Prices Composition Tables for Budgets (PCTB) [58] and other publications [59]. Thus, a factor value of 2 is applied as an inactivity coefficient of loss, c_0, considering only that the work–discharge path is used to transport loads.

3.3. Construction Activities on the Construction Site (E_{CA})

The energy consumed due to construction activities depends on the nature of fuel utilised in the machinery deployed during construction and can be either petroleum-based or electricity-generated [60]. The estimate computed considers consumption due to transportation, assembly, pre-fabrication, and lighting associated with each building component. Electricity consumption is collected from the construction organisation examined. Estimating the expenses associated with petroleum-based machinery requires proper identification and characterisation of the equipment used. To fill the gaps related to the use of equipment and vehicles, a semi-structured and detailed interview is conducted in order to address the main categories of civil construction equipment, as described by PCTB [58]. However, site visits and photographic surveys are also used to clarify doubts. The construction activities are characterised by energy inputs, as seen in Equation (9).

$$E_{CA} = E_{TCS} + E_P + E_L, \quad (9)$$

where

E_{CA}: Represents the total energy consumption associated with construction activities (MJ);
E_{TCS}: Represents the energy consumption associated with the vertical and horizontal transport of materials, losses, components, and people at the construction site (MJ);
E_P: Represents the energy consumption associated with the production activities in general, with the use of the equipment (MJ);
E_L: Represents the energy consumption associated with lighting at the construction site (MJ).

3.3.1. Transportation on the Construction Site (E_{TCS})

This subsection analyses the energy consumed due to using vehicles on the construction site for the horizontal and vertical transportation of loads, employees and labourers. For the consumption of fuel (i.e., diesel and petrol), no added value is used. All the equipment utilised in the project, such as forklifts and manipulators, during the period of the work, are given a usage factor and the energy consumption is calculated. In this research, efficient operation of equipment at the site is accounted for by associating a value of 20% according to results from interviews conducted with machinery operators (i.e., an operating factor of 0.2 is defined to quantify the use of fuel in the equipment). In this way, intra-site transport is computed via Equation (10).

$$E_{TCS} = E_{TCSe} + E_{TCSd}, \quad (10)$$

where

E_{TCS} Represents energy consumption due to intra-site transport (MJ);
E_{TCSe} Represents the estimated energy consumption due to intra-site transportation through the use of equipment supplied by the electricity grid connected to the concessionaire (MJ);
E_{TCSd} Represents the estimated energy consumption due to intra-site transport through the use of diesel-based equipment (MJ).

3.3.2. Construction Activities (E_P)

The energy consumption related to the construction activities involves two parts: (i) soil handling and processing, and (ii) assembly of materials and components. Plant and equipment such as pumps and mixers are included herein since they have been pinpointed in the interviews with technical managers. All the equipment used, such as mini excavators, during the construction phase is associated with a utilisation factor of 0.2. Thus, the energy consumption associated with construction activities is described in Equation (11).

$$E_P = E_{Pe} + E_{Pd}, \quad (11)$$

where

E_P: Represents the overall energy consumption associated with the construction activities, with the use of the equipment (MJ);
E_{Pe}: Represents the estimated electric energy consumption with construction equipment (MJ);
E_{Pd}: Represents the estimated energy consumption of petroleum products due to construction equipment (MJ).

3.3.3. Lighting at the Construction Site (E_L)

The construction site consumes a significant amount of energy that is associated with the mechanical equipment used for lifting, leveling, and transportation, all requiring the use of electricity [61], which is the main source of energy used for lighting purposes at the construction site [62], followed by diesel, petrol, and gas [63].

3.4. Data Quality and Validity

Data quality is one of the key issues to maintain in the inventory processes when conducting an LCA study. This work defines two conditions related to setting up the data quality indicators (DQI) to be considered for the construction of the inventory method adopted in the LCA process:

C1: Analyse the data used to characterise the sub-processes and activities.
C2: Apply the quality indicators at least in the processes considered most significant, based on the results identified.

The DQI used are those proposed by the Pedigree Matrix, adopted by Weidema and Wesnaes [38], based on several indicators (i.e., reliability, completeness, temporal correlation, geographic correlation, and technological correspondence of data).

There are several ways to verify the relevance of data utilised in the LCA approach, including site visits, re-calculation, mass balance, or cross-checking with other sources [38]. This research uses the cross-checking approach through triangulation, which offers the possibility to improve the accuracy of evaluation, and data collected via different forms such as interviews, questionnaires, observation, and field notes, as well as different methods of data analysis [64].

The verification of data in this work is conducted based on comparing the data collected in the work documentation associated with the construction project, with data related to bibliographic references or published construction databases. Output results will be sorted after the triangulation step to address the limitations in inventory processes. Figure 2 illustrates the parameter of reliability in the *Pedigree Matrix*. Figure 2 identifies that data with percentage differences of up to 30% are considered highly reliable [65]. In other words, the reliability parameter presented in Figure 2 is justified because data are built based on measurements and expert reviews; scores can range from 1 to 5. In these terms, score 1 is assigned to the strongest data reliability, while score 5 is assigned to poor data reliability, referring to non-verified data [66].

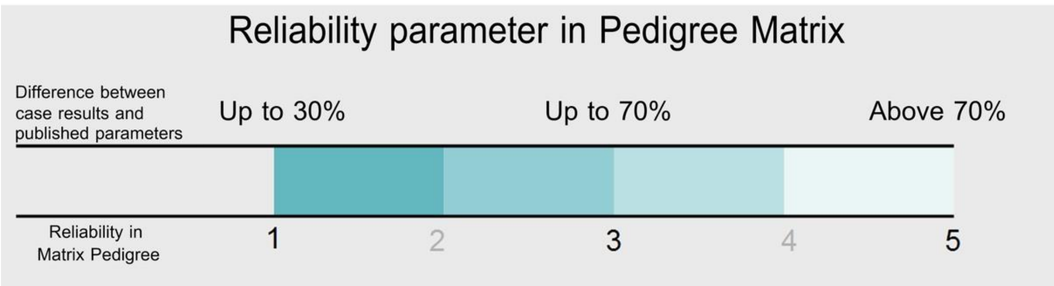

Figure 2. The parameter of reliability in the *Pedigree Matrix*.

4. Case Study

A real case study was adopted to demonstrate the proposed framework's applicability. Construction activities were analysed in detail for a single case chosen as a representative project out of the sample of 16 projects that were evaluated; this was done to maintain the brevity of the discussion. In terms of transportation distances, an average across the 16 projects was adopted in the case study to enforce a representative analysis. The case study of this work is a commercial building composed of 12 floors with a total floor area of 15,665.26 m^2. The function, building area, and height level of each floor are presented in Table 3. The building has been built following quality and environmental management standards specified in ISO 9001 [67], ISO 14,001 [68], the Brazilian Program of Habitat Quality and Productivity [69], and LEED certification [70]. The contractor is a large construction company interested in environmental impacts. Therefore, it makes it easier to obtain the required data to build up the inventory of the database for the case study. The building was chosen to reflect contemporary construction methods utilised in the building and to use the documented information available, including labour, material consumption, and waste in the project. The structure of the building is composed of reinforced concrete: a ribbed slab with pretension is adopted to reduce the number of beams. The external building envelope consists of masonry concrete blocks, along with hollow ceramic bricks. The internal finishes are made of gypsum board. The façades are granite slabs set on mortar and glass, within an aluminum system.

Table 3. Characterisation of the analysed case study building.

Floor Level	Use	Building Area (m^2)	Height Level
4th Underground	pavement	401.96	−13.23
3rd Underground	garage	2451.90	−9.72
2nd Underground	garage	2451.90	−6.66
1st Underground	store deposit and garage	2388.95	−3.06
Ground Floor	stores	1236.19	0.00
1st Floor	commercial rooms	1267.76	3.85
2nd Floor	commercial rooms	1114.22	6.91
3rd Floor	commercial rooms	1114.22	9.97
4th Floor	commercial rooms	1114.22	13.39
Roof	auditorium	1200.94	16.99
Machines and AC	pavement	848.00	20.89
Reservoir	water storage	75.00	24.98
Total Floor Area	15,665.26		

4.1. Transportation of Construction Materials and Components

The energy consumption associated with the transportation activities of materials and components depends mainly on the distances covered and quantities transported. Two parameters are used to characterise transport energy consumption: inter-municipal/interstate travel and municipal/metropolitan travel. The worksheet in the Supplementary File, which is in Portuguese because it comes from Brazilian official sources, summarises the calculation performed, showing the group of components, the displacement distance considered, and the energy consumption identified. As a result, the total energy consumption associated with the transportation of construction materials and components is 1620.59 GJ or 0.103 GJ/m^2, as shown in Table 4.

Figure 3 presents the percentage of energy consumption associated with the transportation of construction materials by building components. For this project, the materials associated with the superstructure phase contribute significantly to the total energy consumption during transport, given the large travel distance for the raw materials. In addition, the wall covering activity also presents a significant consumption, as demonstrated in Table 4 and Figure 3.

Table 4. Results of energy consumption with the transport of materials and components.

Activity	Consumption with Metropolitan Travel (GJ)	Consumption with Inter-Municipal or Interstate Travel (GJ)	Total Consumption (GJ)
Envelope	24.398	265.112	274.087
Iron frames	0.752	-	0.752
Wood frames	0.235	20.161	20.396
Aluminium frames	2.177	-	2.177
Glasses	-	49.141	49.141
Wall coverings	10.816	323.448	334.263
Floor covering	11.466	66.592	78.058
Sills and slabs	0.062	21.128	21.190
Painting	-	11.125	11.125
Benches	0.050	10.038	10.088
Linings	-	17.807	17.807
Superstructure and foundation	331.693	433.433	765.126
Scaffolding and others	6.038	-	6.038
Construction site location	0.033	0.002	0.035
Hydraulic installations	0.20	14.897	15.097
Electrical installations	-	15.210	15.210
Total Consumption	387.92	1248.094	1620.59
Total consumption (GJ/m^2)	-	-	0.103

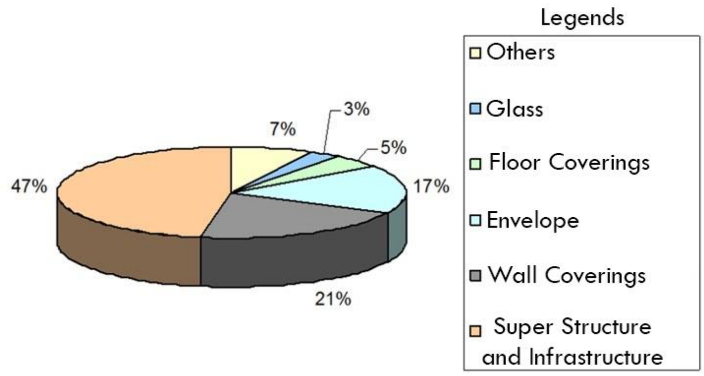

Figure 3. Percentage of energy consumption with transportation of materials and components by building elements.

Figure 4 shows the mass and energy consumption associated with the transportation of construction materials and components that make up the building elements. From Figure 4, it is apparent that the mass of components such as structure, envelope, glass, and walls and floor coverings can highly predict the total energy consumption associated with transport of the material. A relationship exists between the mass of building material and the resulting energy consumption associated with the material transportation. For example, Figure 4 illustrates that approximately 5% of the energy spent on the transportation of materials is associated with the wall coverings. This can be justified by to the use of heavy and non-local materials such as granite. In addition, the superstructure and foundation components represent less than 50% of the energy spent on the transportation of materials. Thus, for certain building elements, the total contribution to the overall energy consumption associated with the transportation of material can be much higher than the total mass percentage contribution of the components making up the building element. Again, this is related to the regional area from which the construction materials are derived; for materials obtained from far away, the travel distance for their transportation is significant.

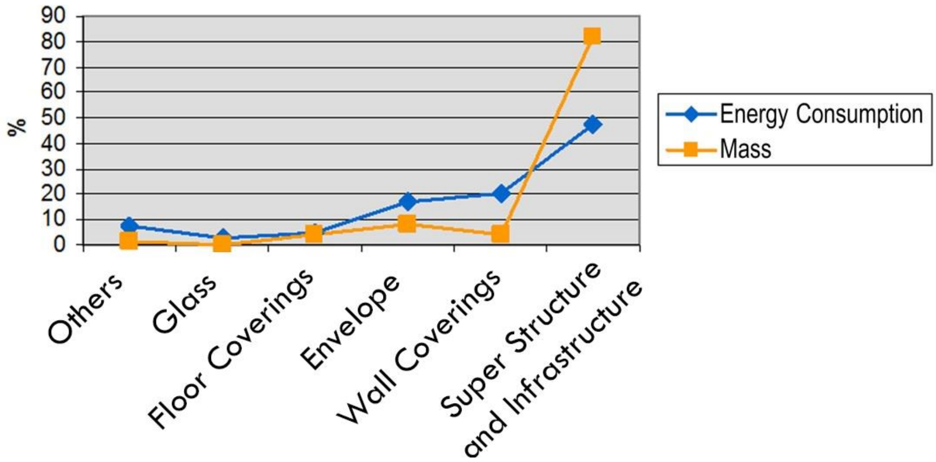

Figure 4. Comparison between mass and energy consumption associated with transport of construction materials and components.

4.1.1. Transportation of Labourers

The building components and associated construction activities for the case study reveal that a total of 33,093.659 work hours is necessary to carry out the construction activities examined in the project. According to Equation (6), the total number of trips needed is 73,590.32. Table 5 presents the composition of man-hours per activity developed.

Table 5. The composition man-hours per building component/activity developed.

Building Component/Activity	Man-Hours	%	Building Component/Activity	Man-Hours	%
Benches	968.99	0.29	Sills and slabs	1167.52	0.35
Wood frames	1998.20	0.60	Iron frames	2886.78	0.87
Aluminum frames	5125.21	1.55	Scaffolding and others	5167.68	1.56
Envelope	13,196.30	3.99	Machinery operation	13,612.05	4.11
Construction site	14,286.23	4.32	Electrical installations	16,801.52	5.08
Painting	18,065.80	5.46	Hydraulic installations	16,929.70	5.12
Floor covering	26,730.40	8.08	Construction management	63,360	19.15
Wall coverings	29,706.00	8.98	Superstructure and foundation	100,164.50	30.27
Total				330,936.59	100%

Figure 5 presents the distance distribution of labourer trips according to the 50 interviews performed. The structured interviews conducted by the authors with technical managers pointed out that the use of transport mode for labour transport across the full schedule of the construction project is as follows: bus mode accounts for 74%, private vehicles account for 20%, and motorcycle accounts for 6%. The average energy consumption of each of these vehicles is characterised by the usage patterns of the vehicles considered. As derived from Figure 5, the average distance per trip identified from the interviews, assuming workers start their travel at their origin, is 44.06 km. Accordingly, the average daily displacement per employee is 89.02 km. Using the formulae presented in Section 3.2, the total number of trips over an average of 44.06 km results in an average energy consumption per traveled distance of 0.575 MJ/km, and the energy consumption associated with the transport of labour is 1,905,480.24 MJ or 1905.48 GJ. Regarding functional equivalent, there is a consumption of 0.122 GJ/m^2 for labour transport activities.

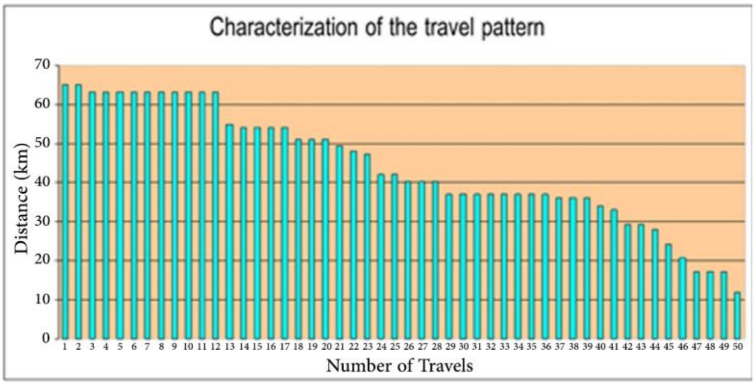

Figure 5. Characterisation of travel in terms of distances, according to structured interviews.

4.1.2. Transportation of Waste due to Damages and Losses

The energy used in transporting waste starts with identifying the amount of waste to be transported. For calculating this amount according to Equation (8), the total mass of the loss data shown in the worksheet presented in Supplementary File shall be used. However, the identified loss has a mass of 1508.49 tons and is distributed in the analysed activities according to Table 6.

Table 6. The identified loss distributed in the analysed activities.

Building Component/Activity	Loss	%	Building Component/Activity	Loss	%
Benches	0.693	0.04	Sills and slabs	0.814	0.05
Wood frames	1.776	0.12	Iron frames	1.573	0.10
Aluminum frames	5.929	0.39	Scaffolding and others	8.33	0.55
Envelope	60.102	3.98	Linings	1.311	0.08
Construction site	0.612	0.04	Electrical installations	6.015	0.40
Painting	1.270	0.08	Hydraulic installations	2.161	0.14
Floor covering	56.487	3.74	glasses	1.967	0.13
Wall coverings	59.829	3.97	Superstructure and foundation	1299.62	86.15
Total				1508.49	100%

The unstructured interviews conducted at this level of the analysis support findings which indicate that the number of companies responsible for transporting waste is rising. Usually, in a construction project, four types of waste discards are conducted during the duration of a project, following the Resolution CONAMA No. 307/2002 specified in Brazil [71]. Class (A) includes waste such as aggregates of bricks, concrete blocks, mortars, sand, and stone; Class (B) includes recycled waste such as plastics, metals, and gypsum; Class (C) includes waste with specific technical standards; and Class (D) includes waste that is not commercially viable for recycling.

For the case study examined, the waste deposit associated with the Sanitary Landfill of the Structural City is 19.5 km from the project's location. The wood waste that makes up Class (B) is sent to a cooperative that develops by-products and is located in the same region as the Sanitary Landfill of the Structural City, so the distance considered for this type of waste is also 19.5 km. Class (D) waste is deposited in suitable containers and discarded only once at the end of the work; the energy consumption of this displacement is disregarded due to its low value. The calculated energy expenditure for transporting damages and losses shows a total mass of 150,849 tons, an average displacement distance of 19.5 km, and a parameter of metropolitan energy consumption of 1.071 MJ/t. km. A coefficient of inactivity (2) is 63,008.11 MJ or 63.01 GJ. Regarding the functional equivalent, there is a consumption of 0.004 GJ/m^2.

4.2. Energy Consumption Associated with Construction Activities Occurring on the Construction Site

The unstructured interviews conducted by the authors have also considered the energy use during construction (i.e., the energy consumed by equipment on the site). The scheme of Table 7 shows the equipment use and the associated energy use type.

Table 7. Equipment used on site and energy.

Equipment Used in the Construction Activities of the Case Study	
Energy Used	Equipment
Electric Power	Air compressor, temporary and permanent pumps, soil compactors, concrete surface finishers, vibrating rulers, dipping vibrators, perforator, concrete mixer, mortar mixer, concrete pump, iron cutting machine, breaking hammer, drilling machine, hand circular saw, soldering machine, elevator.
Fossil Fuels	Small loader, forklift, manipulator, mini excavator, crane.

4.2.1. Electric Power Consumption in the Construction Activities

The obtained electrical energy data corresponds to a 36-month duration of activities on a construction site, with a total constructed area of 15.665.26 m^2. The total consumption of electric energy is 204,588.296 kWh or 736.267 GJ. Accordingly, the defined consumption parameter is 13.06 kWh/m^2 or 0.047 GJ/m^2.

4.2.2. Fossil Fuel Consumption in the Construction Activities

According to unstructured interviews and the characterisation of the activities of earthmoving carried out at the beginning of the work, the calculation of fuel consumption considered two alternative criteria: the calculation from the amount of service performed and the estimated calculation due to the idle time of the equipment. The calculation based on the amount of service performed considers the composition parameters of PCTB (Prices Composition Tables for Budgets) [58], while the calculation associated with the idle time of equipment uses parameters proposed by the National Department of Transport Infrastructure [72]. Table 8 shows the result of the obtained data for the average conditions of application and equipment operation based on the number of yearly working hours [72]; a factor of 0.2 is adopted to indicate, specifically, the Annual parameter of Working Hours (AWH). This work considers the equivalence parameter adopted by the Brazilian Energy Balance [51], where for one m^3 of diesel that corresponds to 35.5 GJ, there is a total consumption of 3210.23 GJ, that is, 0.205 GJ/m^2. As a result, the energy consumption of the functional equivalent is 0.252 GJ/m^2 for the construction activities on the construction site.

Table 8. Equipment energy usage on the construction site.

Equipment	Power (Hp/Watts)	Consumption Parameter (Diesel) L/h	Permanence in the Work (Months)	Usage Parameter	Hours (h)	Factor	Diesel Consumption (L)
Small Loader	49/36.554	5.12	36	200 AWH	6000	0.2	6.44
Manipulator	175/130.550	26.25	24	2000 AWH	4000	0.2	21,000
Mini Excavator	92/68.632	14.4	6	2000 AWH	1000	0.2	2880
Crane	-	38	1	2000 AWH	167	0.2	1269.20
Moto-creator	365/272.290	35.40	-	0.065 h/m^3	1568.84	-	55,536.93
Crawler Tractor	185/138.010	19.50	-	0.0016 h/m^3	38.62	-	753.09
Compactor	6/4.476	1.5	-	0.305 h/m^3	752.59	-	1128.885
Concrete pump 57 m^3/h	100/74.600	20.2	-	4.818, 67 m^3	85	-	1717
Total Consumption							90,429.11

4.3. Data Quality and Interpretations

Data quality analysis of this work is developed based on the verification of the DQI and the application of the Pedigree Matrix. Figure 6 illustrates the identification of data inputs for the characterisation of sub-processes and activities of the DCIEE.

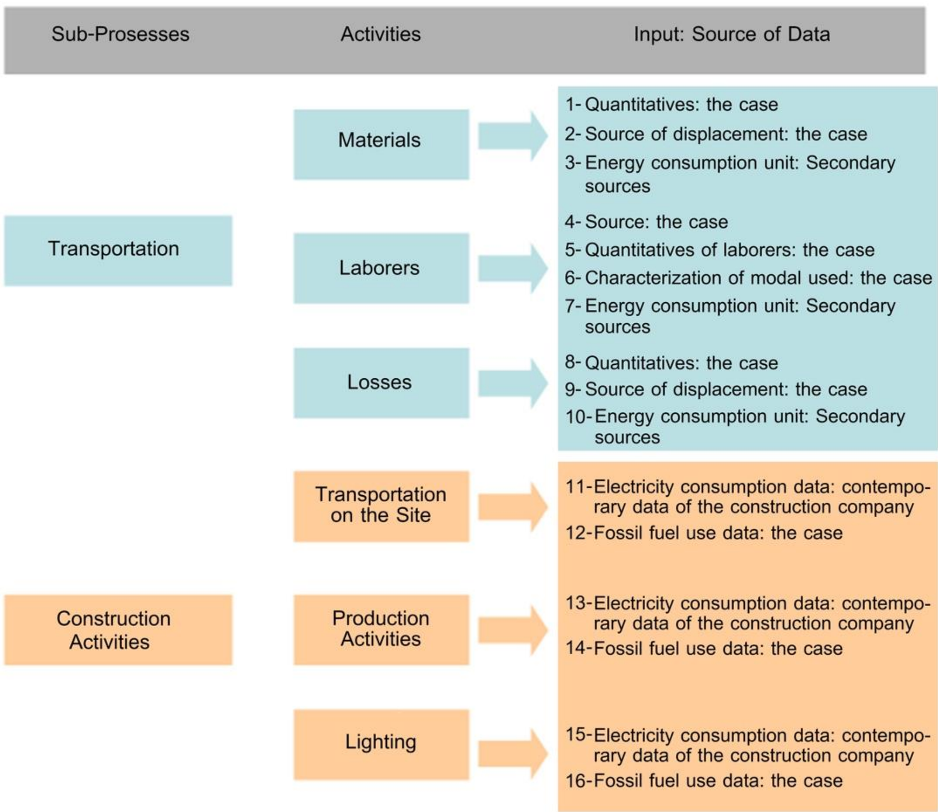

Figure 6. Identification of data inputs for characterisation of subprocesses and activities.

This work identifies 16 groups of data that characterise the various sub-processes and activities associated with a building project. Of these 16 input groups, thirteen are from the construction organisation that conducts the project (i.e., case study), and three are from secondary sources. With the obtained results, the first condition of DQI (C1) has been reached, given that more than 50% of the input data used to characterise the sub-processes and activities originate from the case study. The Pedigree Matrix is applied to all 16 identified input groups to validate the second condition of DQI (C2). The proposed matrix considers the five indicators: reliability, completeness, temporal correlation, geographic correlation, and technological correspondence. To fill this matrix, an analysis of the "reliability" indicator has been conducted through triangulation by comparing the data identified with data published in secondary sources, as shown in Table 9.

Table 9. Triangulation for reliability analysis.

Sub-Process	Activity	Input	Result	Triangulation Parameter	Reliability Status
Transportation of the sub-processes	Transport of construction materials	1	0.103 GJ/m^2	0.260 GJ/m^2 [59] 0.096 GJ/m^2 [73] 0.260 GJ/m^2 * [33] 0.378 GJ/m^2 ** [74] 0.125 GJ/m^2 *** [75]	Up to 70% = 3
		2			
		3			
	Transport of labourers	4	0.122 GJ/m^2	0.845 GJ/m^2 **** [59]	More than 70% = 5
		5			
		6			
		7			
	Transport of damages and losses	8	0.004 GJ/m^2	0.113 GJ/m^2 [59]	More than 70% = 5
		9			
		10			
Activities on the construction site	Transport on the construction site	11	0.252 GJ/m^2	0.004 GJ/m^2 [59] 0.252 GJ/m^2 ** [74] 0.267 GJ/m^2 ** [75]	Up to 30% = 1
		12			
	Production activities	13			
		14			
	Lighting at the construction site	15			
		16			

* Parameters calculated from the plant made available by the authors, secondary and primary energy conversion data presented by the authors. ** It is not clear whether it is primary or secondary energy. *** The data was provided by the author in primary energy, using a factor of 0.9 to transform into secondary energy, considering the source derived from petroleum [33]. **** Consumption estimated by the author using parameters of use of labour by area constructed.

Regarding the results presented in Table 9, it is important to point out the difficulty in comparing the case study under analysis with other cases in the literature, mainly due to the size of the functional equivalent and system boundary for each building case study, as defined within the LCA implemented. As a result, some parameters are considered to have low reliability due to the disaggregated published data. However, it is possible to complete the Pedigree Matrix using the data referring to the "reliability" indicator and considering the technology analysis as representative of contemporary practices to validate the construction system, as shown in Table 10.

As can be seen in Table 10, all inputs, excluding 3 and 10, have the highest temporal correlation, indicating the strongest data reliability. For the geographic correlation, all inputs, excluding 3, 7, and 10, have the highest value indicating data from the area under study with high reliability.

Table 10. Application of the Pedigree Matrix in the data collected in the case study.

Input	Indicator				
	Reliability	**Completeness**	**Temporal Correlation**	**Geographic Correlation**	**Technological Correspondence**
1	3	2	1	1	1
2	3	2	1	1	1
3	3	5	4	3	4
4	5	2	1	1	1
5	5	2	1	1	1
6	5	2	1	1	1
7	5	5	1	2	2
8	5	2	1	1	1
9	5	2	1	1	1
10	5	5	4	3	4
11	1	4	1	1	2
12	1	2	1	1	1
13	1	4	1	1	2
14	1	2	1	1	1
15	1	4	1	1	2
16	1	2	1	1	1

5. Analysis of the Obtained Results

Results of the analysis indicate that the total DCIEE for the applied case study is 0.481 GJ/m^2. In order to understand the suitability of the proposed approach, it is essential to contrast the approach with what has been presented in the literature. The literature presents few works that report on the energy component of buildings in Brazil. Table 11 contrasts studies in the literature that report energy consumption per m^2 of the project due to material transportation in Sweden and Brazil and the result reported by the presented approach. The greatest deviation from the value reported by the approach proposed herein is seen in Tavares [59]. On closer inspection, it appears that such a discrepancy is due to the analysed data concerning the system boundary. On the other hand, the case of Tavares uses solid and perforated ceramic brick walls with a mass of 427.71 kg/m^2. The case study of this work uses gypsum plaster in the internal walls with a mass of 78.30 kg/m^2.

Table 11. Comparison of the results of energy consumed for transporting construction materials between the case study and other studies in the literature.

Source	Energy Consumed for Transportation of Construction Materials	Location of the Case Study
Present Case Study	0.481 GJ/m^2	Brazil
Kuhn [73]	0.096 GJ/m^2	Brazil
Tavares [59]	0.260 GJ/m^2	Brazil
Adalberth [75]	0.126 GJ/m^2	Sweden

Table 12 similarly shows the comparison of the energy consumed as reported by the same studies that were reviewed in Table 11. The energy values are related to the construction activities of the case studies examined. Again, the recognised difference in results between the case study and the case presented by Tavares [59] is due to [63] disregarding some components of construction material movement, such as cranes. In addition, many types of construction equipment were considered in this research since the case analysed required the project to be executed within the shortest possible timeframe. This, in turn, led to an increase in energy consumption in construction activities. Finally, the results show that the energy consumption with the displacement of labour and the use of equipment and machinery in the construction phase significantly impacts the overall DCIEE of the project, and should not, therefore, be disregarded in the LCA processes.

Table 12. Comparison between the results of energy consumption in construction activities of the case under study with published works.

Source	Activities on the Construction Site	Local of the Case Study
Case Study	0.252 GJ/m^2	Brazil
Tavares [59]	0.004 GJ/m^2	Brazil
Adalberth [75]	0.226 GJ/m^2	Sweden
Cole [23]	0.162 GJ/m^2	Canada

Challenges Facing the Application of the LCA Method

Some points challenge the application of the LCA method to quantify embodied energy in construction projects. Bilec [76] indicates that the LCA has been criticised in the sense of being expensive, time-consuming, and using non-scientific assumptions. Zabalza Bribián et al. [75] presented some characteristics of the buildings that hinder the development of studies of LCA; these include the accuracy and arbitrariness of LCA results, lack of standardised interfaces, poor cooperation among the different stakeholders in construction industry, and lack of legal requirements and programs to apply the LCA method. Certain features help make the system boundary difficult to define [77]. For example, the definition of the number of renovations and the consumption of resources with maintenance processes vary significantly; such activities are also influenced by issues such as the type of use, location, and exposure to bad weather. Thus, there is a need to develop less complex methodological procedures for applying LCA concepts in terms of buildings. Davies et al. [26] also identified this deficiency, explaining the non-existence of practical approaches that the actors of the construction industry can effectively adopt.

In terms of simplifying the LCA method in the construction sector, Kellenberger and Althaus [78] developed a study comparing different approaches to verify the validity of methods that evaluate only major construction materials. The results pointed to the relevance of considering transport activities and auxiliary materials (i.e., materials used for maintenance needs only [79]), mainly for certain types of construction systems. On the other hand, Dixit et al. [80] highlighted the lack of reliability presented by the LCA method for buildings' embodied energy. Reasons for reliability issues include the type of energy considered (primary or secondary indicators) and the different ways of characterising the process in the LCA. Improvements require the standardisation of the analysis of the validation processes and procedures, and the analysis of the significance of the cases whose processes are characterised. To minimise the effects of unreliable data an uncertainty analysis method needs to be embedded in the energy analysis, which uses data quality indicators and statistical analysis.

6. Conclusions

This study presented an approach to analyse the quantification of energy consumption in the construction sector through the use of the LCA method, accounting for data unreliability. The novelty of the approach lies in the inventory method used to characterise the energy consumption in the construction stage of building projects at the early design phase via use of data quality goals and data quality indicators. The inventory method developed includes the collection and systematisation of process data that are then processed via DQI to verify the output results. Finally, the proposed method was applied on a case study whose construction technologies are representative of contemporary construction practices in Brazil.

The Pedigree Matrix proposed effectively assessed the data quality of the LCA method based on several indicators such as reliability, completeness, temporal correlation, geographic correlation, and technological correspondence of the data. The results obtained after applying the Pedigree Matrix show that the proposed method can generate high-quality data. Previous work disregarded construction activities in the energy analysis and did not focus on data reliability when conducting LCA; such omissions should be revisited based on the results of this study. Results showed that disregarding some components of construction material movement, such as cranes, along with other construction equipment used in the construction process leads to imprecise embodied energy (DCIEE) estimates for a building. In addition, the results show that the energy consumption with the movement of labour and the use of equipment and machinery in the construction phase significantly impact the overall DCIEE of the project, and should not, therefore, be disregarded in the LCA processes.

A correlation was found to exist between the mass of material transported and the energy consumed by construction activities associated with the material; this can help derive appropriate formations for energy consumption during construction based on the mass of the material consumed during the construction process. In addition, when compared to other studies, the proposed approach was able to better reflect energy consumption of activities taking place during construction since a more accurate breakdown of energy use was considered, along with considering the uncertainty in the data embedded within the LCA approach.

This study focused on the construction phase of buildings when quantifying embodied energy, as many studies in the literature have ignored this. The results highlight the importance of this phase and its real impact on the entire lifespan of buildings. Some of the limitations of this study include lack of integration of the LCA method adopted with Building Information Modeling (BIM) tools, Multi-Criteria Decision Analysis, or even several optimisation methods. This can be a viable direction for future works to characterise embodied energy in buildings.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings13010052/s1.

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