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STUDY OF EMBODIED ENERGY IN HEALTHCARE CENTER CONSTRUCTION

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Abstract. The tendency to build Net-Zero Energy Buildings increases the need to know and control the energy used in them. This research aims to identify and quantify the energy used in the construction of healthcare centres and propose indicators based on different operational variables. For this purpose, seven healthcare centres built between 2007 and 2010 were analysed, and the energy embodied in the manufacturing, transport and placement of materials on-site, including the final tests and commissioning of the building, were calculated. The results show that the average embodied energy is 9.97 GJ per unit of built area, 0.011 for each euro invested in construction and 2.18 GJ for each user. Emissions per worker, construction working hour, electrical power and energy consumed were also typified, and different reference indicators were proposed. Equations have also been devised using multivariate regression to determine the embodied energy of a healthcare centre according to its built area (m^2), investment in construction (€) and the number of users (No). The building elements with the most embodied energy were also identified, and the authors found that the average embodied energy is 29.31 times higher than that consumed in a year at the healthcare centre.

Keywords: healthcare engineering, building projects, embodied energy, healthcare buildings, design benchmarks, civil engineering.

Introduction

The materials and processes chosen for the construction of a building are critical when classifying it as sustainable (Singh & Lazarus, 2018). Therefore, the energy embodied in the construction, which includes the energy used in the manufacture of the materials, their transport and that used by the machinery during the execution of the work, must be considered (Dixit, 2019).

Many buildings called Net-Zero Energy Building (NZEB) do not count their embodied energy as a result of the construction and manufacturing process of the materials they incorporate (Bontempi, 2017). They only consider the energy used in operating the building, ignoring the energy related to the construction and commissioning and its components.

In the European Union, buildings account for 40% of energy consumption (European Commission, 2019). However, in common architectural practice, the environmental cost of materials is generally not analyzed (Nydahl et al., 2019), mainly due to the lack of available data, loyalty to conventional construction methods and the complexity of calculating the energy incorporated (Qarout, 2017).

Healthcare centers differ from hospitals in that the former are not intended for either hospitalization or surgeries (García-Sanz-Calcedo et al., 2018). Their design, construction and maintenance show high technical requirements, provided the impact of the building construction on both productivity of healthcare workers and patient recovery is accounted for (Reay et al., 2017).

Focusing efforts on reducing the operational energy consumption of buildings can increase the energy and emissions used in the construction (Yeo et al., 2016). The reason behind this is that the reduction in operating energy sometimes comes with an increase in the emissions incorporated into the building caused by the use of materials that absorb much power in their manufacture but achieve savings in the operating phase (Ramesh et al., 2010).

Chastas et al. (2016) observed this in their review of the literature on energy incorporated into residential and

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NZEB buildings. They observed that in passive buildings, the proportion of energy incorporated varies within a range of 11% to 33%, which reaches the limits of incorporated energy of both a conventional building and a low energy building.

Furthermore, Giordano et al. (2017) evaluated Embodied Energy (EE) and Operational Energy (OE) in a NZEB. The effect of EE in the energy analysis of buildings in some cases represented 50% of all Primary Energy Demand. Ding (2004) compiled works by several authors and concluded that the energy embodied in residential buildings ranges from 3.6 to 8.76 GJ/m^2, in commercial buildings from 3.4 to 19.00 GJ/m^2 and in university centers from 6 to 13 GJ/m^2. Praseeda et al. (2019) quantified a maximum of 2.8 GJ/m^2 of energy embodied in rural households in India. Dascalaki et al. (2020) evaluated embodied energy in various buildings between 3.2 GJ/m^2 to 7.1 GJ/m^2 with an average of 5.6 GJ/m^2 and also observed that the EE increases from lower to higher performance buildings.

Chang et al. (2012) calculated that the energy incorporated in an educational building in China was 6.3 GJ/m^2. This result is higher than the average value of residential buildings (5.5 GJ/m^2) but much lower than in commercial buildings (9.2 GJ/m^2) in the UK, Australia and Japan. Azari and Abbasabadi (2018) studied the energy embodied in buildings and concluded that the energy embodied in the construction of residential buildings ranged from 1.7 to 8.76 GJ/m^2. Estokova et al. (2017) estimated the energy embodied in the construction of residential buildings in Slovakia at between 2.50 and 4.43 GJ/m^2. Reddy et al. (2014) indicated that the energy embodied in the construction of conventional brick masonry buildings is between 3 and 4 GJ/m^2.

The results of these authors differ significantly from one another, with excessively high intervals. However, the energy embodied in healthcare buildings was never evaluated, possibly because quantifying the emissions incorporated in the construction of a building is complex and consumes more resources than measuring the operational energy (Dixit, 2017). Therefore, there is no precedent of similar studies that quantify the energy embodied in the construction of healthcare centers, rendering this research novel in this respect.

This research, therefore, aims to identify and quantify the energy incorporated into the construction of healthcare centers and propose emission indicators based on different operational variables, typical of this type of building. The stages that cause most of the energy embodied in the construction of healthcare centers are identified, and indicators will also be available for benchmarking in the design and drafting process of healthcare center projects. The evaluation of the energy embodied in the construction of a healthcare center will improve the decision-making process in the design phase and allow a sustainable choice of materials used in its construction.

1. Methodology

Seven healthcare centers located in Extremadura (Spain), designed between 2006 and 2009 and built between 2007 and 2010, were analyzed using similar construction materials, facilities, processes and construction typology. Specifically, they had the following facilities: Heating, Ventilation and Air-Conditioning (HVAC), Domestic Hot Water (DHW), Cold Water for Human Consumption (CWHC), electricity and others. The operational variables of the healthcare centers analyzed are shown in Table 1.

Table 1. Healthcare centers analyzed

Centre	Built area (m^2)	Annual users	Workers	Year of construction
1	1 515	13 359	22	2009
2	1 328	4 700	16	2007
3	2 824	17 844	40	2009
4	3 192	14 951	34	2008
5	2 367	16 500	22	2009
6	1 877	6 984	19	2008
7	1 647	5 350	24	2009

All the building projects were drafted under the same Spanish legal regulations. The most significant regulations affecting them were the Technical Building Code (Código Técnico de la Edificación, 2006) and the Spanish Regulation on Thermal Installation in Buildings (Ministerio para la Transición Ecológica, 1998).

Each healthcare building was visited to verify that it coincided with the detailed design to ensure the accuracy of the data analyzed. All the buildings were constructed with a reinforced concrete structure and unidirectional slabs, braced footing, air-conditioning with heat pumps, a high level of thermal insulation, inverted roof, aluminum carpentry with double glazing, terrazzo flooring, finishing of walls in smooth plastic paint, transformation center with medium voltage connection, a generator set, among others. Building facades were made of a 25-cm-thick double hollow brick layer internally plastered with cement mortar, a manufactured-on-site polyurethane stiff foam embedded on the internal side with a minimum density of 35 kg/m^3 and 3-cm mean thickness and an extra 7-cm-thick double hollow brick partition, coated with cement mortar. All the roofs were non-trafficable roofs made up of a 10-cm-thick aerated concrete layer for slope formations, 2-cm-thick mortar cement, a 40-mm-thick thermal insulation coating, an elastomer bitumen plate composed of a 60 g/m^2 fiberglass felt frame and an elastomer bitumen coating in both sides, a bitumen asphalt plate with a 160 g/m^2 polyester frame, a 3 kg/m^2 plastic film and a 5-cm-thick 20/40 cobble gravel layer.

The emissions associated with demolition were not considered, and the analysis was limited to three stages: the extraction of materials, the supply of materials and the construction stage, including the final tests and commissioning of each healthcare center. The construction materials supply stage included the amount of energy associated with the extraction, processing and production of said construction materials. Transport included the movement of workforce and materials to and from the site. The construction phase included the energy associated with the entire healthcare center construction process, including final testing and commissioning of the facilities. Since healthcare centers were located in the same region and they were built with almost the same materials, similar materials travelled distances were considered. Therefore, the average material travelled distance could be determined by calculating the mean road distance from the point of manufacture to the healthcare center construction site and grouped by the material type. An average distance of 250 kilometers was considered.

The operational variables used in the research were the built area (m^2), the number of users (No), the number of workers in each healthcare center (No), execution cost (€), the total number of hours used in construction (h), electrical power installed (kW) and annual energy consumption (kWh) of each healthcare center.

The average energy consumed annually in each healthcare center was obtained from the energy audits carried out in each of the buildings between 2012 and 2015.

The BEDEC database of the Institute of Building Technology of Catalonia (Instituto de Tecnología de la Construcción [ITEC], 2019) was used to determine the energy embodied in each healthcare center. The construction materials were inventoried according to the detailed design, and each material was calculated discretely and classified by chapters.

The total embodied energy in each HVAC healthcare facility was calculated by adding the embodied energy of each material used in the project and multiplied by the total material amount, also adding the energy from the construction and transportation process, according to Eqn (1).

$$E = \sum_{i=1}^{n} (e_i \times j_i) + c_f + c_t + c_c, \quad (1)$$

where E corresponds to the total amount of energy embodied in the HVAC healthcare facility, expressed in kg; e_i represents the embodied energy of each material; j_i the amount of material used; e_f the energy incorporated into the building during the construction process; e_t the energy incorporated from the transport of materials; and e_c indicates the energy incorporated from the building construction.

The total number of hours worked, and the effective duration of work for each construction project was calculated and classified by professional category, considering a working day of 8 hours a day, 5 days a week. A Site Manager, two supervisors, an administrative assistant and two guards were also considered as indirect workforce.

When determining emissions related to worker mobility, the authors assumed that the construction site was located in an area far from the city center, with no access to urban transport and an average daily distance travelled by vehicles was estimated at 20 km. Table 2 shows the energy used per kilogram of load and kilometer travelled, according to the means of transport used (A. Atmaca & N. Atmaca, 2015).

Table 2. Energy used per kilometer and means of transport

Method of Transport	Energy (MJ/(kg.km))
Deep-sea transport	0.216
Truck (road)	2.275
Coastal vessel	0.468
Class railroads	0.275

The determination coefficients R^2 were calculated to establish the degree of relationship between the different variables. An analysis of the variance was performed for the multivariable linear regression models using the F-distribution, and the Student t-distribution was calculated to determine the significance of each independent variable in the different models.

A partial correlation analysis was performed to study the relationship between two variables when more than two variables are present and the other factors are fixed and controlled. When the control variable (C) is fixed, the partial correlation coefficient between variables A and B is calculated using Eqn (2):

$$r_{ABC} = \frac{r_{AB} - r_{AC} r_{BC}}{\sqrt{1 - r_{AC}^2} \cdot \sqrt{1 - r_{BC}^2}}, \quad (2)$$

where r_{AB} is the conventional correlation coefficient between A and B, r_{AC} is the conventional correlation coefficient between A and C and r_{BC} is the conventional correlation coefficient between B and C.

2. Results

The results obtained during the research process are presented in an orderly manner below.

2.1. Relationship between the energy embodied in the construction and the built area of a healthcare center

Figure 1 shows the relationship between the energy embodied in the construction and the built area of a healthcare center.

Equation (3), which is valid for buildings between 1,000 and 4,000 m^2, can be applied to determine the average energy embodied in the construction process of a healthcare center:

$$EE = 6.66S + 6{,}838.50, \quad (3)$$

where EE is the energy embodied in the construction process of a healthcare center stated in GJ and S is the built area of the building in m^2.

2.2. Relationship between the embodied energy and investment in the construction of a healthcare center

The relationship between the embodied energy and investment in the construction of a healthcare center is shown in Figure 2.

Equation (4) can be applied to determine the average energy embodied in the construction process of a healthcare center:

$$EE = 6.21\ I + 8{,}665.70, \quad (4)$$

where *EE* is the energy embodied in the construction process of a healthcare center stated in GJ, and *I* is the investment required for such construction in euros.

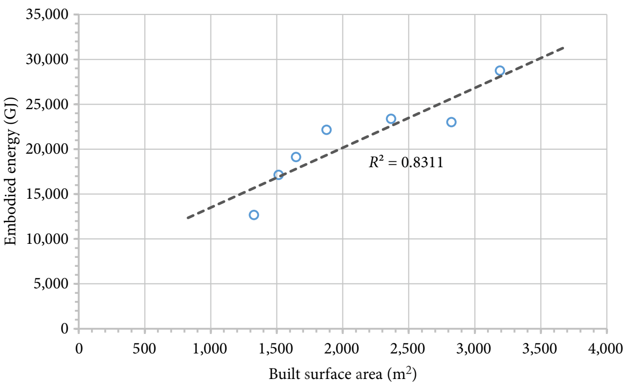

Figure 1. Relationship between the energy embodied in the construction and the built area of a healthcare center

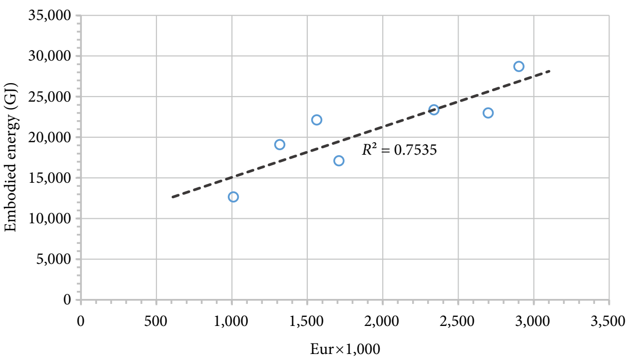

Figure 2. Relationship between the embodied energy and investment in the construction of a healthcare center

2.3. Analysis of embodied energy by stage

Figure 3 shows the average percentage impact, standard deviation and percentiles of embodied energy in the construction process of a healthcare center, classified by construction stages.

The authors noted that the phase that incorporates most energy in the construction of healthcare centers is the manufacture of the construction materials (95.15%), followed by transport (3.34%), and construction (1.29%).

2.4. Embodied energy by operating variable. Reference indicators

Table 3 shows the mean, standard deviation and percentiles of each of the reference indicators analyzed in the study: area (m^2), euro invested in the construction (€), number (No), number of workers, number of healthcare center users, average annual energy consumption (kWh), installed electrical power (kW) and hour of work used in the construction phase.

The most appropriate indicators are the area and investment (euros). Indicators based on installed electrical power or average annual energy consumption cannot be applied until the building is in the use phase. Indicators based on the number of users and number of workers can vary substantially.

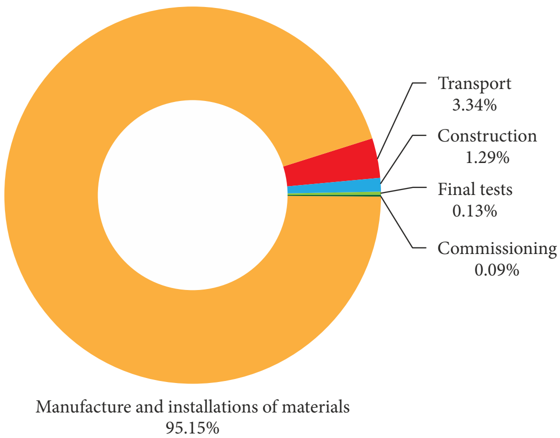

Figure 3. Percentage impact by stages of embodied energy in the construction of a healthcare center

Table 3. Carbon emission indicators per functional unit

Ratio	Average	Standard deviation	Percentiles				
			10%	25%	50%	75%	90%
GJ/m²	9.97	1.17	8.66	9.26	9.87	10.73	11.49
GJ/€	0.011	0.002	0.009	0,010	0.010	0.012	0.013
GJ/users	2.19	0.88	1.29	1.35	1.92	2.93	3.33
GJ/workers	858.76	181.90	696.48	784.08	795.78	953.49	1,103.55
GJ/kWh	0.106	0.019	0.087	0.091	0.098	0.116	0.132
GJ/kW	65.82	12.17	52.97	55.94	63.24	72,41	81.27
GJ/h	0.644	0.082	0.560	0.612	0.644	0.689	0.733

2.5. Embodied energy depending on the type of work

Figure 4 shows the average percentage of energy embodied in a healthcare center, according to the type of work carried out on the site.

The highest embodied energy appears to be concentrated in the structure and roof (38.52%), followed by masonry, insulation and carpentry (29.85%) and earthwork, sanitation and foundation (15.54%).

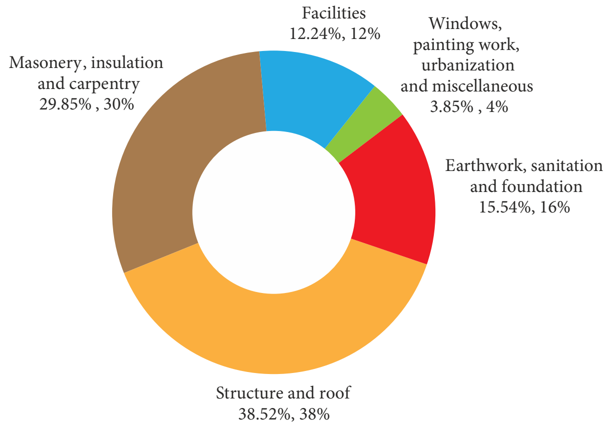

Figure 4. Distribution of embodied energy in a healthcare center according to the type of construction work

2.6. Analysis according to the intensity of use

The construction elements that caused the highest amount of energy embodied in the construction process of a healthcare center were identified and are shown in Figure 5.

The structure, masonry, foundation and roof are the chapters of a healthcare construction project with more embodied energy per m^2, followed by masonry, thermal insulation, wall and ceiling cladding and carpentry (doors and windows). These phases account for about 70% of the total energy embodied in the construction process of a healthcare center. Materials must, therefore, be selected appropriately during the design process.

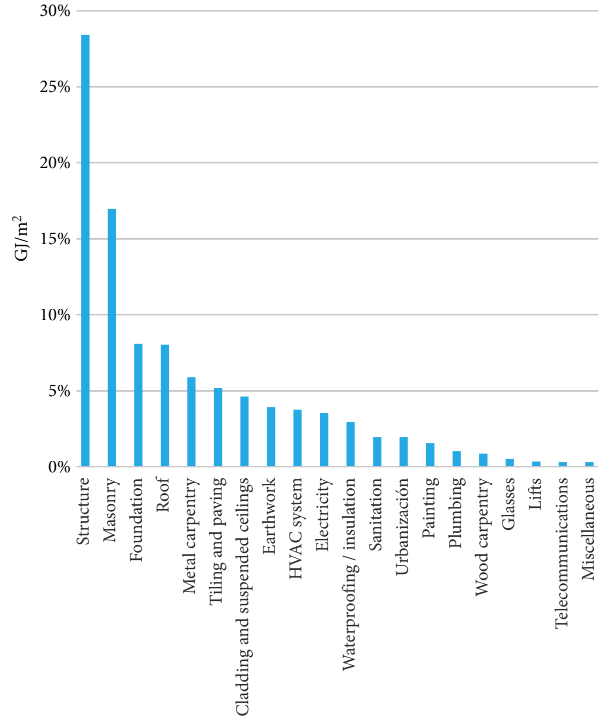

Figure 5. Percentage distribution of embodied energy by intensity of use

2.7. Relationship between the annual energy consumed and the energy embodied in the construction of a healthcare center

The relationship between the annual energy consumed and the energy embodied in the construction of a healthcare center is shown in Figure 6.

The authors also determined that there is a correlation between the embodied energy and annual operation energy variables. This type of building has 29 times more embodied energy than that consumed in a year, which is more than a considerable amount.

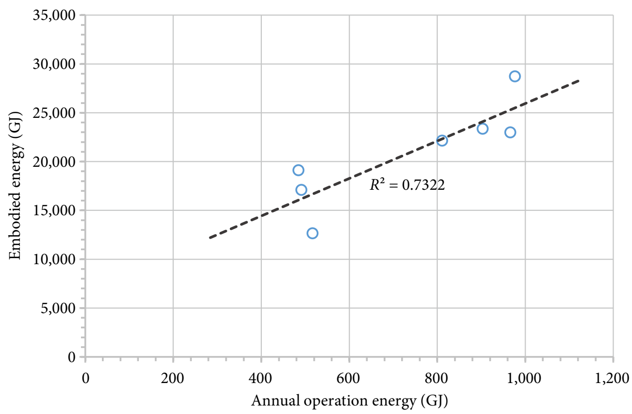

Figure 6. Relationship between the annual operation energy and the energy embodied in the construction of a healthcare center

2.8. Multivariable linear regression models

Several multivariable linear regression models were analyzed, given the proven high correlation between the variables. The dependent variable is the energy embodied in the construction (*EE*), for which the following independent variables have been collated: built area (m^2), number of users (No), number of workers (No), execution cost (euros), number of hours spent on construction (h), electrical power installed (kW) and annual energy consumption (kWh) of each healthcare center. Of all the possible combinations of independent variables, the 3 models shown in Eqns (5), (6) and (7) were relevant with a statistical criterion of $p\text{-}value < 0.05$.

$$EE = 7.42S - 0.78I + 6{,}733.30; \quad (5)$$

$$EE = 7.43S - 0.13U + 6{,}694.84; \quad (6)$$

$$EE = 11.42I - 0.75U + 7{,}346.00. \quad (7)$$

These equations allow determining the embodied energy (*EE*) stated in GJ, according to the variables: built area (*S*) stated in m^2, investment in construction (*I*) stated in euros (EUR) and/or number of users (U). The equations are valid for healthcare centers between 1,000 and 4,000 m^2.

Table 4 shows the regression statistics, contrasted by the F-distribution. No multivariable models of 3 or more independent variables were found.

Table 4. Statistics of the regression models

Equation	Correlation	R^2	Error (GJ)	F (p-value)
5	0.9122	0.8320	2,583.35	0.02820
6	0.9164	0.8397	2,523.45	0.02568
7	0.9379	0.8797	2,186.14	0.01446

3. Discussion

There are grounds to say that to determine the embodied energy of a healthcare center, the most suitable functional unit is the built area (m^2). The construction phase of a healthcare center cannot be assessed from an environmental perspective with the number of users and workers. However, both indicators are necessary to determine the environmental impact in the use phase, and have, therefore, been included as results of this research. Emissions per euro invested in construction have also proven to be an appropriate indicator to measure its sustainability.

Any of the three regression models proposed in this paper are valid for determining the energy embodied in healthcare centers. However, it should be borne in mind that depending on the number of users, some buildings may be under- or over-evaluated. Therefore, this should be verified before applying the model, or equation 5 should be used, which does not include this variable.

To control the total embodied energy of a project, one must try to use local materials, which minimize transport requirements and guarantee a better adaptation to the natural environment (Guo et al., 2019). In addition, transport processes must be reduced, selecting means that use non-fossil fuels and optimizing material transport processes. Finally, low energy embodied materials must be chosen. These are materials that make minimal use of energy for extraction, production, transformation and disposal (McGain & Naylor, 2014).

Transport accounts for 3.34% of the total energy embodied in the construction stage. Their impact can be reduced by using collective transport and hybrid vehicles (Hu et al., 2020). An appropriate measure is for subcontractors to share trucks and reduce trips.

It has been proven that the materials manufacture phase incorporates most energy in the construction of healthcare centers. Therefore, to minimize it, the right choice of materials is critical in the design phase of the building. This coincides with the conclusions of other authors. For example, Rosselló-Batle et al. (2015) showed that 75% of the energy incorporated into a building came from only a small group of the building's components. They proved that the values of incorporated energy could be reduced by between 14% to 29% with simple replacements and between 1,770 and 4,160 tons of CO_2 could be avoided altogether and emitted to the atmosphere with budget increases of less than 8%. Furthermore, Carretero-Ayuso and García-Sanz-Calcedo (2018) compared LCA roofing systems, observing that embodied energy can be reduced without increasing the cost of a building by using the right choice of materials.

Strategies based on the circular economy and the reuse of building materials can substantially reduce the energy embodied in construction (Pomponi & Moncaster, 2017). Designing elements with products that can be manufactured again with lower energy consumption substantially decreases the energy embodied in a building (García-Sanz-Calcedo & Pena-Corpa, 2014).

The authors concluded that in terms of energy expenditure, it is more cost-effective to build on existing buildings than to build from scratch. They estimated that this could save up to 60% of the energy used in the construction process (Baker et al., 2017). Going overboard with equipment and the redundancy of installations also significantly increase environmental emissions. However, redundancy is essential to ensure resilience in the event of emergencies or natural disasters in healthcare buildings (Salah et al., 2018).

There are multiple barriers to implementing energy-efficient technologies in public hospitals in all countries (Seifert et al., 2019). For example, in China, economic incentives, appropriate technology and applicable laws and regulations are not sufficiently supported by the government and have become the most important barriers to energy efficiency improvement (Wang et al., 2016).

Zhai and Helman (2019), on their part, explored the possible impacts of climate change that are directly related to the building's energy consumption. Mandley et al. (2015) proposed four measures to reduce energy embodied in a building, achieving significant reductions in energy consumption in the short and medium-term in the UK, with projections estimating resources and embodied energy savings of 4.7% and 6.4%, respectively, by 2020 and 9.3% and 28.6% by 2030.

Due to the effects of the construction sector on the environment, accounting for energy embodied in building projects is becoming a vital consideration in project development approval processes (Kibwami & Tutesigensi, 2015).

The regulations should incorporate a maximum limit for embodied energy in the construction phase of buildings, which would favor the choice of materials with less environmental impact in the design process (Gustavsson & Joelsson, 2010). In any case, the convenience of rehabilitating healthcare buildings must be evaluated (Alba-Rodríguez et al., 2017).

This paper is useful as a reference for the design or renovation of healthcare buildings. The results can be extrapolated to other types of buildings with similar facilities and quality of materials; also, to other countries with similar legal regulations and construction techniques.

Future work should focus on determining the recurrent embodied energy in healthcare centers and setting criteria to optimize their management.

Conclusions

The energy embodied in the construction process of healthcare centers was evaluated. The results show that the energy embodied in construction should be considered as a tool to minimize the extraction and exploitation of non-renewable raw materials.

Equations have been proposed using multivariate regression techniques to determine the embodied energy of a healthcare center according to its built area (m^2), investment in construction (€) and the number of users (No). Reference indicators were also determined based on other variables. The authors determined that the average energy embodied in the construction is 9.97 GJ/m^2, 0.011 GJ/euros or 2.18 GJ/user. Emissions per worker, construction working hour, electrical power and energy consumed were also typified, and different reference indicators were proposed.

Moreover, the building elements with the most embodied energy were also identified. The authors detected that under normal weather and operating conditions, the measured embodied energy is 29.31 higher than that consumed by the building in a year.

It has become clear that there is a need to use a new energy rating index for buildings, which considers the amounts of embodied energy. At present, to achieve an NZEB rating, only the operational energy initially intended for the building is used.

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Author contributions

Conceptualization, J.G.S.C.; methodology, J.G.S.C.; formal analysis, J.P.A.F.; investigation, N.S.N. and J.G.S.C.; resources, J.G.S.C.; writing – original draft preparation J.P.A.F and N.S.N.; writing–review and editing, J.G.S.C.; visualization, A J.G.S.C.; supervision, J.G.S.C.; funding acquisition, J.G.S.C.

Disclosure statement

Authors declare that they have not any competing financial, professional, or personal interests from other parties.

References

Alba-Rodríguez, M. D., Martínez-Rocamora, A., González-Vallejo, P., Ferreira-Sánchez, A., & Marrero, M. (2017). Building rehabilitation versus demolition and new construction: Economic and environmental assessment. *Environmental Impact Assessment Review*, *66*, 115–126. https://doi.org/10.1016/j.eiar.2017.06.002

Atmaca, A., & Atmaca, N. (2015). Life cycle energy (LCEA) and carbon dioxide emissions ($LCCO_2A$) assessment of two residential buildings in Gaziantep, Turkey. *Energy and Buildings*, *102*, 417–431. https://doi.org/10.1016/j.enbuild.2015.06.008

Azari, R., & Abbasabadi, N. (2018). Embodied energy of buildings: A review of data, methods, challenges, and research trends. *Energy and Buildings*, *168*, 225–235. https://doi.org/10.1016/j.enbuild.2018.03.003

Baker, H., Moncaster, A., & Al-Tabbaa, A. (2017). Decision-making for the demolition or adaptation of buildings. *Proceedings of the Institution of Civil Engineers-Forensic Engineering*, *170*(3), 144–156. https://doi.org/10.1680/jfoen.16.00026

Bontempi, E. (2017). A new approach for evaluating the sustainability of raw materials substitution based on embodied energy and the CO_2 footprint. *Journal of Cleaner Production*, *162*, 162–169. https://doi.org/10.1016/j.jclepro.2017.06.028

Carretero-Ayuso, M. J., & García-Sanz-Calcedo, J. (2018). Comparison between building roof construction systems based on the LCA. *Revista de la Construcción*, *17*(1), 123–136. https://doi.org/10.7764/RDLC.17.1.123

Chang, Y., Ries, R. J., & Lei, S. H. (2012). The embodied energy and emissions of a high-rise education building: A quantification using process-based hybrid life cycle inventory model. *Energy and Buildings*, *55*, 790–798. https://doi.org/10.1016/j.enbuild.2012.10.019

Chastas, P., Theodosiou, T., & Bikas, D. (2016). Embodied energy in residential buildings-towards the nearly zero energy building: A literature review. *Building and Environment*, *105*, 267–282. https://doi.org/10.1016/j.buildenv.2016.05.040

Código Técnico de la Edificación. (2006). *Technical building code* (in Spanish).

Dascalaki, E., Argiropoulou, P., Balaras, C. A., Droutsa, K. G., Kontoyiannidis, S., & Koubogiannis, D. (2020). On the share of embodied energy in the lifetime energy use of typical Hellenic residential buildings. *IOP Conference Series: Earth and Environmental Science*, *410*, 012070. https://doi.org/10.1088/1755-1315/410/1/012070

Ding, G. (2004). *The development of a multi-criteria approach for the measurement of sustainable performance for built projects and facilities* [PhD thesis]. University of Technology, Sydney.

Dixit, M. K. (2017). Life cycle embodied energy analysis of residential buildings: A review of literature to investigate embodied energy parameters. *Renewable and Sustainable Energy Reviews*, *79*, 390–413. https://doi.org/10.1016/j.rser.2017.05.051

Dixit, M. K. (2019). Life cycle recurrent embodied energy calculation of buildings: A review. *Journal of Cleaner Production*, *209*, 731–754. https://doi.org/10.1016/j.jclepro.2018.10.230

Estokova, A., Vilcekova, S., & Porhincak, M. (2017). Analyzing embodied energy, global warming and acidification potentials of materials in residential buildings. *Procedia Engineering*, *180*, 1675–1683. https://doi.org/10.1016/j.proeng.2017.04.330

European Commission. (2019). *Energy efficient buildings*. https://ec.europa.eu/energy/en/topics/energy-efficiency/energy-performance-of-buildings

García-Sanz-Calcedo, J., Al-Kassir, A., & Yusaf, T. (2018). Economic and environmental impact of energy saving in healthcare buildings. *Applied Sciences*, *8*(3), 440. https://doi.org/10.3390/app8030440

García-Sanz-Calcedo, J., & Pena-Corpa, S. (2014). Comparativa entre sistemas constructivos de huecos para ascensores en función del ACV. *Dyna*, *89*(1), 98–105. https://doi.org/10.6036/5800

Giordano, R., Serra, V., Demaria, E., & Duzel, A. (2017). Embodied energy versus operational energy in a nearly zero energy building case study. *Energy Procedia*, *111*, 367–376. https://doi.org/10.1016/j.egypro.2017.03.198

Guo, S., Zheng, S., Hu, Y., Hong, J., Wu, X., & Tang, M. (2019). Embodied energy use in the global construction industry. *Applied Energy*, *256*, 113838. https://doi.org/10.1016/j.apenergy.2019.113838

Gustavsson, L., & Joelsson, A. (2010). Life cycle primary energy analysis of residential buildings. *Energy and Buildings*, *42*(2), 210–220. https://doi.org/10.1016/j.enbuild.2009.08.017

Hu, X., Zhang, X., Tang, X., & Lin, X. (2020). Model predictive control of hybrid electric vehicles for fuel economy, emission reductions, and inter-vehicle safety in car-following scenarios. *Energy*, *196*, 117101. https://doi.org/10.1016/j.energy.2020.117101

Instituto de Tecnología de la Construcción. (2019). Banco ITEC2019. *Datos Ambientales* [Environmental data]. Barcelona, Spain.

Kibwami, N., & Tutesigensi, A. (2015). Exploring the potential of accounting for embodied carbon emissions in building projects in Uganda. In *Proceedings of the 31st Annual ARCOM Conference* (pp. 327–336). Association of Researchers in Construction Management.

Mandley, S., Harmsen, R., & Worrell, E. (2015). Identifying the potential for resource and embodied energy savings within the UK building sector. *Energy and Buildings*, *86*, 841–851. https://doi.org/10.1016/j.enbuild.2014.10.044

Mcgain, F., & Naylor, C. (2014). Environmental sustainability in hospitals–a systematic review and research agenda. *Journal of Health Services Research & Policy*, *19*(4), 245–252. https://doi.org/10.1177/1355819614534836

Ministerio para la Transición Ecológica. (1998). *Reglamento de Instalaciones Térmicas en los Edificios* (in Spanish).

Nydahl, H., Andersson, S., Åstrand, A. P., & Olofsson, T. (2019). Environmental performance measures to assess building refurbishment from a life cycle perspective. *Energies*, *12*(2), 299. https://doi.org/10.3390/en12020299

Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment: A research framework. *Journal of Cleaner Production*, *143*, 710–718. https://doi.org/10.1016/j.jclepro.2016.12.055

Praseeda, K. I., Venkatarama Reddy, B. V. V., & Mani, M. (2019). Embodied and operational energy of rural dwellings in India. *International Journal of Sustainable Energy*, *38*(3), 227–237. https://doi.org/10.1080/14786451.2017.1418742

Qarout, L. (2017). Reducing the environmental impacts of building materials: *Embodied energy analysis of a high-performance building* [Doctoral thesis]. University of Wisconsin-Milwaukee.

Ramesh, T., Prakash, R., & Shukla, K. K. (2010). Life cycle energy analysis of buildings: an overview. *Energy and Buildings*, *42*(10), 1592–1600. https://doi.org/10.1016/j.enbuild.2010.05.007

Reay, S., Collier, G., Kennedy-Bueno, J., Old, A., Douglas, R. & Bill, A. (2017). Designing the future of healthcare together: Prototyping a hospital co-design space. *CoDesign*, *13*(4), 227–244. https://doi.org/10.1080/15710882.2016.1160127

Reddy, B. V. V., Leuzinger, G., & Sreeram, V. S. (2014). Low embodied energy cement stabilised rammed earth building-A case study. *Energy and Buildings*, *68*, 541–546. https://doi.org/10.1016/j.enbuild.2013.09.051

Rosselló-Batle, B., Ribas, C., Moià-Pol, A., & Martínez-Moll, V. (2015). Saving potential for embodied energy and CO_2 emissions from building elements: A case study. *Journal of Building Physics*, *39*(3), 261–284. https://doi.org/10.1177/1744259114543982

Salah, M., Osman, H., & Hosny, O. (2018). Performance-based reliability-centered maintenance planning for hospital facilities. *Journal of Performance of Constructed Facilities*, *32*(1), 04017113. https://doi.org/10.1061/(ASCE)CF.1943-5509.0001112

Seifert, C., Koep, L., Wolf, P., & Guenther, E. Life cycle assessment as decision support tool for environmental management in hospitals: A literature review. *Health Care Management Review*, *46*(1), 12–24. https://doi.org/10.1097/HMR.0000000000000248

Singh, R., & Lazarus, I. J. (2018). Energy-efficient building construction and embodied energy. In A. Shukla & A. Sharma (Eds.), *Sustainability through energy-efficient buildings* (pp. 89–107). CRC Press. https://doi.org/10.1201/9781315159065-5

Wang, T., Li, X., Lia, P.-C. & Fang, D. (2016). Building energy efficiency for public hospitals and healthcare facilities in China: Barriers and drivers. *Energy*, *103*, 588–597. https://doi.org/10.1016/j.energy.2016.03.039

Yeo, Z., Ng, R., & Song, B. (2016). Technique for quantification of embodied carbon footprint of construction projects using probabilistic emission factor estimators. *Journal of Cleaner Production*, *119*, 135–151. https://doi.org/10.1016/j.jclepro.2016.01.076

Zhai, Z. J., & Helman, J. M. (2019). Implications of climate changes to building energy and design. *Sustainable Cities and Society*, *44*, 511–519. https://doi.org/10.1016/j.scs.2018.10.043