Optimizing $\text{CO}_2$ emissions from heating and cooling and from the materials used in residential buildings, depending on their geometric characteristics

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ABSTRACT

The objective of this research was to obtain the environmentally optimal design of a building with the following starting conditions: constant constructed surface, constant volume, square floor layout, and a variable number of floors. For this purpose, the study evaluated the impact of $\text{CO}_2$ emissions stemming from the energy needed to maintain the building at a constant temperature of 19 °C in winter and 25 °C in the summer. Furthermore, one of the results was the $\text{CO}_2$ emissions curve from the manufacturing of the materials used in the construction of the building and the building envelope.

The energy consumed to cool and heat the building was calculated by means of the simplified method specified in the ISO/DIS/13790 standard. The building was thus regarded as a monozone with the consequent simplifications. The matrix method was used to calculate the building’s structure for the purpose of obtaining the $\text{CO}_2$ emissions from the concrete and steel needed to construct it. The result obtained was the curve representing the $\text{CO}_2$ emissions, depending on building height. The source of these emissions was the energy consumption from heating and cooling as well as from the manufacture of construction materials.

The results of the study indicated that the useful life of the building was a very important factor to take into account. The methodology used in this study could be used by building designers to design buildings with an optimal height for the reduction of negative environmental impacts.

1. Introduction

Environmental degradation is currently at great risk because of factors related to population increase, resource consumption, industrial activity, etc. This situation is causing serious environmental problems such as acid rain or the progressive disappearance of the ozone layer. Such problems are directly related to the emission of substances into the atmosphere as a consequence of fossil fuel combustion or the use of CFCs [1]. Many authors have mentioned the impact of the construction sector and industry on the environment, and have underlined how the responsible selection of building materials can minimize environmental impact [2]. The effect of construction activities can be assessed by calculating the $\text{CO}_2$ emissions as measured in kg or Tn.

The conception of an architectural project and its optimization from a social, economic, technical, and environmental perspective has been studied by various authors. For example, Depecker et al. obtained the ratio of building shape to energy consumption, based on the values resulting from the variation of the shape coefficient defining the geometric properties of the building [3]. AlAnzi et al. [4] analyzed the impact of building shape in relation to heating requirements in the case of offices. They studied the impact of building shape, orientation, and window surface. A series of equations were thus obtained that related energy consumption to these variables. Such energy consumption is directly related to atmospheric emissions, and depends on the energy generation sources.

Chel and Tiwari [5,6] studied the heat performance of dome-shaped houses constructed with environmentally-friendly building materials such as adobe. Based on embodied energy analysis, the energy payback time for the mud-house was found to be 18 years. The annual heating and cooling energy saving potential of the mud-house was calculated at 1481 kW h/year and 1813 kW h/year. The energy saving potential for both heating and cooling came to 5.2 metric tonnes/year.

Climate design is one of the most effective methods of reducing energy costs in building construction [7]. It is thus possible to design energy-efficient buildings by focusing on design and/or construction elements [8]. This justifies the efforts of the various agents that participate in the construction of such buildings. The
The best opportunities to apply “ecological” design strategies to a building can be found in the conceptual design phase. This research study analyzed a series of rectangular-shaped buildings with a variable number of floors for a constant value of the total constructed surface \( S \) and building volume \( V \). The main objective was to obtain results that would ultimately allow project designers to optimize building design by taking into account not only the energy consumption, but also the environmental impacts resulting from the consumption of building materials, once the surface necessities were defined.

It was thus possible to obtain the optimal curve for minimizing \( \text{CO}_2 \) emissions to the atmosphere. This includes the sum of emissions to maintain the building within a comfortable temperature range and the emissions produced in the manufacturing process of the building construction materials.

Our research was carried out in the following phases:

- Definition of building shape. It was decided that the total constructed surface \( S \) should be constant, and the number of floors variable.
- Calculation of the \( \text{CO}_2 \) emissions produced to heat, cool, and maintain the building within a certain temperature range in summer as well as winter.
- Calculation and dimensioning of the frame elements of the building and the measurement of units that compose the building roof, frame elements, and façades.

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**Nomenclature**

- **A** profile section
- **b_t** reduction factor
- **E** longitudinal deformation modulus
- **E_G** transversal deformation modulus
- \( H_{T,k} \) heat transfer coefficient by transmission of element \( k \)
- \( H_{V,k} \) heat transfer coefficient by ventilation of air of flow element \( k \)
- \( I_i \) inertia modulus in reference to the axis \( i (i=x,y,z) \)
- \( k \) element \( k \) to adjacent space
- **N** total number of floors
- \( n_i \) number of floors
- \( Q_{G,H} \) total heat sources for the heating mode (in MJ)
- \( Q_i \) internal heat sources in the given time period (in MJ)
- \( Q_{k,k} \) heat from internal heat source \( k \) in the zone during a given month or season (in MJ)
- \( Q_{U,k} \) heat from internal heat source (in MJ)
- \( Q_{L,H} \) total heat transfer for the heating mode (in MJ)
- **Q_{NH}** building energy need for heating (in MJ)
- \( Q_S \) solar heat sources during a given month (in MJ)
- \( Q_{S,c} \) sum of solar heat sources during a given month (in MJ)
- \( Q_{U,H} \) total heat transfer by ventilation (in MJ)
- \( S \) total constructed surface \( (m^2) \) (fixed value)
- **t** duration of the calculation period (days)
- \( V \) total building volume (fixed value)
- \( \theta_i \) internal temperature \( °C \)
- \( \theta_{e,k} \) external temperature of the adjacent space \( k \), \( °C \)
- \( \theta_{w,k} \) supply temperature of the air flow element \( k \) entering the building by ventilation or infiltration, \( °C \)

**Greek symbols**

- \( \eta_{G,H} \) dimensionless gain utilization factor
- \( \lambda_{\text{max}} \) maximum slenderness
- \( \nu \) Poisson coefficient

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Estimate of the CO\textsubscript{2} emissions from the manufacturing of building construction material. In this sense, the useful life of a building was considered to be 50 years [9].

The results obtained were used to obtain the curve of total emissions, which reflected the impact of the heating and cooling systems and the overall construction process. The result was the optimal building height for the starting conditions.

2. Definition of the shape parameter

For the purposes of this research, a series of rectangular-shaped buildings were analyzed with a variable number of floors for a constant value of the Total Constructed Surface (S) and Building Volume (V) (see Fig. 1). The number of floors \( n \) varied from \( i = 1 \) to \( N \) floors. To determine the value of \( N \), we analyzed the mean value of the number of floors for the 100 tallest residential buildings in the world [10]. The value obtained was \( N = 60 \) floors.

Having defined \( N \) for a vertical distance between floor slabs of 3.2 m, the building layout dimensions were obtained for each number of floors, \( n_i \) \( (i = 1, \ldots, 60) \). Our main guideline was the DB-SE-AE [11], which states that conventional buildings are not sensitive to the dynamic effects of the wind. In order for these effects to be negligible, the slenderness, \( \lambda = h/a \) (where \( h \) = building height and \( a \) = building layout width), should be less than 6.

The initial data used to calculate energy consumption as well as the construction costs measured in CO\textsubscript{2} emissions were the following:

- Total constructed surface: \( S = 75,000 \text{ m}^2 \)
- Inside volume: \( 213 \text{ m}^3 \)
- Building layout: square-shaped
- Maximum slenderness: \( \lambda_{\text{max}} = 6 \)
- Vertical distance between floors: 3.2 m
- Number of floors (variable): 1–60

Fig. 1 shows the dimensions of the building to be studied for those cases where the number of floors is equal to 60, 25 and 15.

Once the building dimensions were defined, we then obtained the values of the emissions from energy consumption for heating and cooling, as measured in kg of CO\textsubscript{2}. The next step was to calculate the frame and foundations, and then measure the building units (i.e. foundation, frame, envelope, and roof). The purpose of this was to assess the environmental impact of the construction materials. This was calculated for a useful life of 50 years, as measured in CO\textsubscript{2} emissions for the series of buildings whose geometric characteristics are listed in the following table: (Table 1).

3. Energy consumption

This section describes the method used for the design and evaluation of the thermal and energy performance of the buildings in this study. The objective was to calculate the energy needed to maintain a building at a given temperature in both winter and summer.

The energy needed to heat and cool a building was calculated according to the procedure outlined in the standard ISO/TC 163/SC 2: Thermal performance of buildings—Calculation of energy use for space heating and cooling [12]. For this study, we used a quasi-steady state method to calculate the heat balance over a time period of sufficient length for dynamic effects to be negligible (typically one month or one season).

The monthly calculation gave accurate results on an annual basis, but the results for individual months near the beginning and end of the heating and cooling season reflected significant relative errors. This method was chosen for our study because our goal was to obtain and compare the annual energy consumption of different building shape profiles.

For this study, each building was regarded as a monozone since initial conditions were specified for maintaining buildings at a set
temperature (19 °C for heating and 25 °C for cooling). These conditions were the same as those in the ISO/DIS 13790 standard:

a) set-point temperatures for heating of spaces vary by more than 4 K;
b) spaces are mechanically cooled and set-point temperatures for cooling spaces differ by more than 4 K;
c) different heating or cooling systems service different areas of the conditioned space, as specified by prEN wi 7–10 and 12;
d) different ventilation systems service different areas of the conditioned space, as specified by prEN wi 20/21. None of these ventilation systems services at least 80% of the building or zone. If at least 80% of the building or zone is serviced by one ventilation system, the other spaces in the building or zone shall be regarded as serviced by the main ventilation system.

The inputs needed to obtain energy consumption demands for heating as well as cooling are the following:

- transmission and ventilation properties
- internal heat sources and solar properties
- climate
- description of the building as well as its components, systems, and use
- data related to heating, cooling, hot water, ventilation, and lighting systems
- energy losses dissipated or recovered in the building (internal heat sources and recovery of ventilation heat loss)
- air flow rate and temperature of ventilation supply air

The initial calculation data were the following:

- The global thermal characteristics of each wall were:
  - Floor: 0.58 W/m²K
  - Ceiling: 0.49 W/m²K
  - Front wall: 0.57 W/m²K
  - Glazing: 3.5 W/m²K
  - Thermal inertia:
    - Air renewal rate (daily average rate): 0.5
    - Internal energy gains: 4 W/m²
    - Normal heating regime: 19 °C
    - Normal cooling regime: 25 °C

3.1. Energy demand for heating

The energy required for space heating for each time period (one month) was calculated with the following formula:

\[ Q_{\text{NH}} = Q_{U,H} - \eta_{\text{G,H}} Q_{S,H} = (Q_T + Q_{V}) - \eta_{\text{G,H}} (Q_{T} + Q_{S}) \]

where \( Q_{\text{NH}} \geq 0 \), and where for each month:

\( Q_{\text{NH}} \) is the building energy required for heating, in MJ;
\( Q_{U,H} \) is the total heat transfer for the heating mode in MJ.
\( Q_T \) is the total heat transfer by transmission in MJ:
\[ Q_T = \sum k(H_{T,k} \cdot (\theta_{z,k} - \theta_{e,k})) \cdot t \] where \( H_{T,k} \) is the heat transfer coefficient by transmission of element \( k \) to adjacent space(s), environment or zone(s) with temperature \( \theta_{e,k} \) in W/K; \( \theta_{z,k} \) is the internal temperature of the building or building zone in degree Celsius; \( \theta_{e,k} \) is the temperature of the adjacent space, environment, or zone of element \( k \) in degree Celsius; \( t \) is the duration of the calculation period.

\( Q_{V} \) is the total heat transfer by ventilation in MJ:
\[ Q_{V} = \sum k(H_{V,k} \cdot (\theta_{z,k} - \theta_{e,k})) \cdot t \] where \( H_{V,k} \) is the heat transfer coefficient by ventilation of air flow element \( k \) entering the zone with a given supply temperature \( \theta_{s,k} \); \( \theta_{z,k} \) is the supply temperature of the air flow element \( k \) entering the building or building zone by ventilation or infiltration in degree Celsius.

\( Q_{G,H} = Q_{T} + Q_{S} \) are the total heat sources for the heating mode. \( Q_{T} \) is the sum of internal heat sources over the given time period:
\[ Q_{T} = \sum Q_{i,k} + \sum (1 - b_{j}) Q_{s,uj} \] where \( Q_{i,k} \) is the heat from internal heat source \( k \) in the conditioned zone during the month or season considered in MJ; \( Q_{s,uj} \) is the heat from an internal heat source \( l \) in an adjacent unconditioned space during the month or season considered in MJ; \( b_{j} \) is the reduction factor for the adjacent unconditioned space with internal heat source \( i \), as defined in ISO/DIS 13789:2005.

\( Q_{T} \) is the sum of solar heat sources over the given time period:
\[ Q_{T} = Q_{s,c} + \sum (1 - b_{j}) Q_{s,uj} \] where \( Q_{s,c} \) is the sum of solar heat sources during the month or season considered in the conditioned zone in MJ; \( Q_{s,uj} \) is the sum of solar heat sources during the month or season considered in the adjacent unconditioned space \( j \) in MJ; \( b_{j} \) is the reduction factor for the adjacent unconditioned space \( j \) with solar heat source \( i \), as defined in ISO/DIS 13789:2005.

\( \eta_{\text{G,H}} \) is the dimensionless gain utilization factor.

3.2. Energy demand for cooling

Similarly, for each building zone, the energy demand for cooling for each time period (one month or one season) was calculated with the following formula:

\[ Q_{\text{NC}} = Q_{C} - \eta_{\text{L,C}} Q_{L,C} \]

where \( Q_{\text{NC}} \geq 0 \) and where (for each building zone, and for each month or season):

\( Q_{\text{NC}} \) is the building energy required for cooling in MJ.

### Table 2

<table>
<thead>
<tr>
<th>Floor number</th>
<th>Energy consumption in Spain (%)</th>
<th>(kg CO₂/MJ)</th>
<th>(g CO₂/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>15.30</td>
<td>0.096</td>
<td>346.67</td>
</tr>
<tr>
<td>Oil</td>
<td>52.20</td>
<td>0.073</td>
<td>263.96</td>
</tr>
<tr>
<td>Natural gas</td>
<td>13.00</td>
<td>0.056</td>
<td>200.94</td>
</tr>
<tr>
<td>Nuclear energy</td>
<td>12.80</td>
<td>0.000</td>
<td>0.00</td>
</tr>
<tr>
<td>Renewable energy</td>
<td>6.70</td>
<td>0.000</td>
<td>0.00</td>
</tr>
</tbody>
</table>
The calculation was performed monthly, and did not take into account aspects such as temperature stratification at heights and the necessary energy increase of elements in the installation, such as load loss in pipelines due to increased length, pumping, etc. Consequently, the data obtained are approximate within the context of these limitations (Fig. 2).

The shape of the curve (see Fig. 4) is explained by the fact that the simplified model regards the building as a monozone and that the exterior surface of the building measured as the sum of the surfaces of the façade, roof, and floor slab in contact with the ground follows the function represented in Fig. 5. As the number of floors increases, the curve follows a practically linear tendency for the starting conditions (i.e. constant floor layout surface and building volume and variable number of floors).

4. Frame calculation of the building

The following model was used to calculate the building frame. The frame was made up of bar-type elements in the case of columns, beams, and floor slabs as well as finite triangular elements that model the walls. The calculation of the stresses on these elements was performed by using a matrix stiffness method. For this purpose, the relation between the stresses and deformations of the bar elements was assumed to be linear, and six degrees of freedom per node was also contemplated. For each element, there was a relation between the stresses acting on it and the displacement, according to the relation, \( f = K \cdot D \), where \( K \) is the stiffness matrix of the element and \( D \) is the displacements of the nodes. The following example shows the stiffness matrix of a bar-type element, where it is possible to observe the profiles used for the calculation of stresses.

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Where:

\[
K = \begin{pmatrix}
\frac{E \cdot A_s}{L} & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{12 \cdot E \cdot I_x}{L^3} & 0 & 0 & 0 & 0 \\
0 & 0 & \frac{12 \cdot E \cdot I_y}{L^3} & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{G \cdot I_z}{L} & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{6 \cdot E \cdot I_y}{L^2} & 0 \\
0 & -\frac{6 \cdot E \cdot I_x}{L^2} & 0 & 0 & 0 & 0
\end{pmatrix}
\]

A is the profile section;
E is the longitudinal deformation modulus;
\(i_i\) is the inertia modulus in reference to the axis \(i\) (i = x, y, z);
\(G = E / (1 + \nu)\) is the transversal deformation modulus and \(\nu\) is the Poisson coefficient.

This method was used to formulate and resolve the equation system or stiffness matrix of the frame, thus obtaining the displacements of the nodes, due to action of the set of loads. This made it possible to obtain the stresses on the nodes, depending on the displacements, \(\{F\} = [K] \cdot \{d\}\) (Fig. 6).

This calculation was performed with the software application, CYPECAD [15]. Fig. 5 shows the model of a 40-floor building. The values of the actions considered for the dimensioning of the frame elements were the following:

Once the frame had been calculated, the quantities of steel and concrete per m² were then obtained for each of the building profiles as well as for the façade and roof surfaces. Figs. 7 and 8 show the quantities of steel and concrete in the foundation and frame elements as well as the sum of the two.

The discontinuities in the graph that represents the quantity of steel in the foundations are due to the change in foundation profile from isolated footing to slab foundation. The quantity per m² was also calculated for each of the following units: concrete (strength 25 kN/m²; 30 kN/m²; 40 kN/m²; 50 kN/m²); wood formwork in slabs and columns; brickwork façades; plaster; paint; aluminum joinery for windows and non-traffic-bearing roofs on a layer of light concrete (average thickness of 10 cm) to support slopes made from geotextile fabric and bitumen with polyurethane insulation.

5. Calculation of the emissions from construction materials

Once established the units in the frame, envelope, and roof, it was possible to obtain the materials of which they were made. Table 3 lists the atmospheric emissions in kg/CO₂ generated during the manufacturing process of each construction element [16].

These values were used to obtain the CO₂ emissions from the different items or building construction units: m³ of concrete slabs,

### Table 3: Atmospheric emissions in kg/CO₂ generated during the manufacturing process of each construction element

<table>
<thead>
<tr>
<th>Material</th>
<th>Emissions (kg/CO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete slabs (strength 25 kN/m²)</td>
<td>4.7 kN/m²</td>
</tr>
<tr>
<td>Concrete slabs (strength 30 kN/m²)</td>
<td>6.2 kN/m²</td>
</tr>
<tr>
<td>Concrete slabs (strength 40 kN/m²)</td>
<td>3.0 kN/m²</td>
</tr>
<tr>
<td>Concrete slabs (strength 50 kN/m²)</td>
<td>1.0 kN/m²</td>
</tr>
</tbody>
</table>

Fig. 5. External surface of the building, roof, and flooring in contact with the ground, depending on the number of floors.

Fig. 6. Model for the calculation of the frame: Building of 40 floors.
3. Results

In accordance with our initial hypotheses and in the case of CO₂ emissions from the heating and cooling of the building, we found the optimal value for a building with four floors. After this value, energy consumption increased, following the curve shown in Fig. 4.

6. Conclusions

In the case of emissions produced during the manufacturing processes of building construction materials, an optimal value was obtained, for a five-floor building. The long time periods corresponding to the useful life of a building (i.e. 50 years) cause the annual emissions from construction materials to be very low in comparison to the emissions produced to keep temperatures constant (Fig. 10).

Regarding the emissions from construction materials, an important increase was observed when the building height increased from six to seven floors. The reasons for this were the increase in m² of concrete because of the decision to use slab foundations instead of isolated footing, due to geotechnical factors (see Fig. 9).

For the design conditions (square floor layout, constructed surface, constant volume, and variable building height), the

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environmental impact for two factors studied, measured in CO₂ emissions, was found to be minimal for buildings of 4, 5, and 6 floors (see Fig. 10). As previously mentioned, the weight of the CO₂ emissions from the manufacture of building materials is related to the useful life of the building structure. When this period is increased, the value of the emissions from these materials is very low in comparison to the total. In our study, when the building had four floors, the emissions were 9%. As the height of the building increased, this value decreased (Fig. 11).

Based on the importance of the useful life of the building in the percentage of CO₂ emissions due to building materials, a series of calculations were made that resulted in the set of curves shown in Fig. 12. The building surface and volume are fixed values, the number of floors is constant, and the useful life of the building is taken as a variable. We were thus able to obtain the value of the curves corresponding to buildings with 1, 4, 5, 15, 25, 45 and 50 floors.

The results in Fig. 12 show that for periods longer than 10 years, the emissions remain practically constant, or what is the same, the CO₂ emissions from building construction materials are very slight.

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The impact on the environment is largely due to the emissions caused by the heating and cooling of the building.

7. Conclusions

The design phase of a building is the best time to implement strategies for the reduction of energy consumption in a building during its useful life. In the initial phases of the life cycle of the project, it is possible to model the building’s design as well as choose the construction materials so that the structure will be more energy-efficient. In our study, where the design criteria were to maintain the building surface and volume constant and vary the number of floors, the most effective solutions were found when the building had 4–6 floors.

Furthermore, in regards to the aspects focused on in our research (i.e. CO₂ emissions from heating and cooling and the construction materials used), it was found that the useful life of the building was a crucial factor. Consequently for useful life periods of over ten years, the weight of the emissions into the atmosphere during the manufacturing process was very slight in comparison to the sum of both factors (heating and cooling and materials). The methodology in this research can be used by building designers to calculate optimal building height with a view to minimizing the environmental impact from the CO₂ emissions produced by the manufacturing of building materials as well as those due to the heating and cooling of a building during its useful life.

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