Building and Environment xxx (2011) 1–9

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Optimizing CO_2 emissions from heating and cooling and from the materials used in residential buildings, depending on their geometric characteristics

Javier Ordóñez [a,*], Vijay Modi [b]

[a] Department of Civil Engineering, University of Granada, E.T.S. de Ingenieros de Caminos,.C/Severo Ochoa s/n, 18071 Granada, Spain
[b] Department of Mechanical Engineering, Columbia University, NY, USA

ARTICLE INFO

Article history:
Received 29 October 2010
Received in revised form
16 April 2011
Accepted 21 April 2011

Keywords:
Energy consumption
Heating and cooling demand
Building shape
CO_2 emissions

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 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 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 CO_2 emissions from the concrete and steel needed to construct it. The result obtained was the curve representing the 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 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

* Corresponding author. Tel.: +34 958 249441.
E-mail address: javiord@ugr.es (J. Ordóñez).

0360-1323/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.buildenv.2011.04.030

Nomenclature

A	profile section
b_l	reduction factor
E	longitudinal deformation modulus
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)
$Q_{i,k}$	heat from internal heat source k in the zone during a given month or season (in MJ)
$Q_{i,u,l}$	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 in a given time period
$Q_{S,C}$	sum of solar heat sources during a given month (in MJ)
$Q_{s,u,j}$	solar heat sources during a given month (in MJ)
Q_T	total heat transfer by transmission (in MJ)
Q_V	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)
θ_i	internal temperature °C
$\theta_{e,k}$	external temperature of the adjacent space k, °C
$\theta_{s,k}$	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
λ_{max}	maximum slenderness
υ	Poisson coefficient

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 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 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.

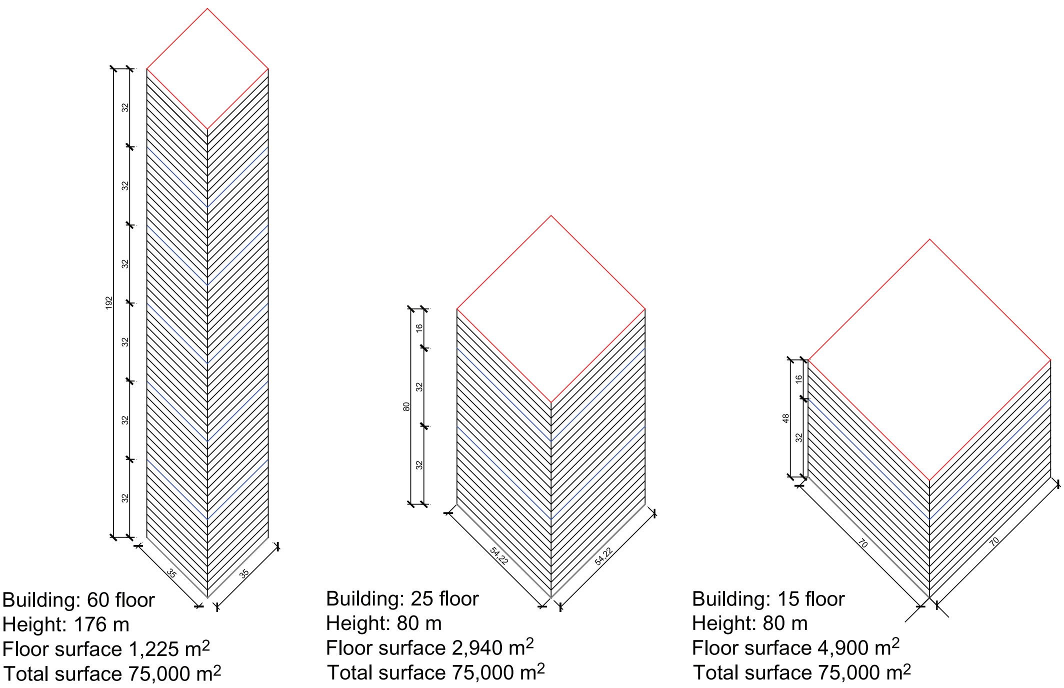

Fig. 1. Variation of shape with height.

Please cite this article in press as: Ordóñez J, Modi V, Optimizing CO_2 emissions from heating and cooling and from the materials used in residential buildings, depending on their geometric characteristics, Building and Environment (2011), doi:10.1016/j.buildenv.2011.04.030

- Estimate of the CO_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_i 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_2 emissions were the following:

- Total constructed surface: $S = 75\ 000\ m^2$
- Inside volume = 213 150 m^3
- Building layout: square-shaped
- Maximum slenderness: $\lambda_{max} = 6$
- 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_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_2 emissions for the series of buildings whose geometric characteristics are listed in the following table: (Table 1).

Table 1
Geometric dimensions of the buildings with a constant constructed surface (75 000 m^2).

Building parameter					
Number of floors	Total floor surface (m^2)	Width (m)	Length (m)	Height (m)	Slenderness
1	73 500.0	271.11	271.11	3.20	0.012
2	36 750.0	191.70	191.70	6.40	0.033
3	24 500.0	156.52	156.52	9.60	0.061
4	18 375.0	135.55	135.55	12.80	0.094
5	14 700.0	121.24	121.24	16.00	0.132
6	12 250.0	110.68	110.68	19.20	0.173
7	10 500.0	102.47	102.47	22.40	0.219
8	9187.5	95.85	95.85	25.60	0.267
9	8166.7	90.37	90.37	28.80	0.319
10	7350.0	85.73	85.73	32.00	0.373
11	6681.8	81.74	81.74	35.20	0.431
12	6125.0	78.26	78.26	38.40	0.491
13	5653.8	75.19	75.19	41.60	0.553
14	5250.0	72.46	72.46	44.80	0.618
15	4900.0	70.00	70.00	48.00	0.686
16	4593.8	67.78	67.78	51.20	0.755
17	4323.5	65.75	65.75	54.40	0.827
18	4083.3	63.90	63.90	57.60	0.901
19	3868.4	62.20	62.20	60.80	0.978
20	3675.0	60.62	60.62	64.00	1.056
21	3500.0	59.16	59.16	67.20	1.136
22	3340.9	57.80	57.80	70.40	1.218
23	3195.7	56.53	56.53	73.60	1.302
24	3062.5	55.34	55.34	76.80	1.388
25	2940.0	54.22	54.22	80.00	1.475
26	2826.9	53.17	53.17	83.20	1.565
27	2722.2	52.17	52.17	86.40	1.656
28	2625.0	51.23	51.23	89.60	1.749
29	2534.5	50.34	50.34	92.80	1.843
30	2450.0	49.50	49.50	96.00	1.939
31	2371.0	48.69	48.69	99.20	2.037
32	2296.9	47.93	47.93	102.40	2.137
33	2227.3	47.19	47.19	105.60	2.238
34	2161.8	46.49	46.49	108.80	2.340
35	2100.0	45.83	45.83	112.00	2.444
36	2041.7	45.18	45.18	115.20	2.550
37	1986.5	44.57	44.57	118.40	2.656
38	1934.2	43.98	43.98	121.60	2.765
39	1884.6	43.41	43.41	124.80	2.875
40	1837.5	42.87	42.87	128.00	2.986
41	1792.7	42.34	42.34	131.20	3.099
42	1750.0	41.83	41.83	134.40	3.213
43	1709.3	41.34	41.34	137.60	3.328
44	1670.5	40.87	40.87	140.80	3.445
45	1633.3	40.41	40.41	144.00	3.563
46	1597.8	39.97	39.97	147.20	3.683
47	1563.8	39.55	39.55	150.40	3.803
48	1531.3	39.13	39.13	153.60	3.925
49	1500.0	38.73	38.73	156.80	4.049
50	1470.0	38.34	38.34	160.00	4.173
51	1441.2	37.96	37.96	163.20	4.299
52	1413.5	37.60	37.60	166.40	4.426
53	1386.8	37.24	37.24	169.60	4.554
54	1361.1	36.89	36.89	172.80	4.684
55	1336.4	36.56	36.56	176.00	4.814
56	1312.5	36.23	36.23	179.20	4.946
57	1289.5	35.91	35.91	182.40	5.079
58	1267.2	35.60	35.60	185.60	5.214
59	1245.8	35.30	35.30	188.80	5.349
60	1225.0	35.00	35.00	192.00	5.486

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

Please cite this article in press as: Ordóñez J, Modi V, Optimizing CO_2 emissions from heating and cooling and from the materials used in residential buildings, depending on their geometric characteristics, Building and Environment (2011), doi:10.1016/j.buildenv.2011.04.030

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 Wm^2/K
○ Ceiling	0.49 Wm^2/K
○ Front walls	0.57 Wm^2/K
○ Glazing	3.5 Wm^2/K
• Thermal inertia	400 kJ/m^2
• Air renewal date (daily average rate):	0.5
• Internal energy gains	4 W/m^2
• 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:

$$Q_{NH} = Q_{L,H} - \eta_{G,H} \cdot Q_{G,H} = (Q_T + Q_V) - \eta_{G,H} \cdot (Q_i + Q_S)$$

where $Q_{NH} \geq 0$, and where for each month:

Q_{NH} is the building energy required for heating, in MJ;
$Q_{L,H} = Q_T + Q_V$ is the total heat transfer for the heating mode in MJ.

Q_T is the total heat transfer by transmission in MJ; $Q_T = \sum k\{H_{T,k} \cdot (\theta_i - \theta_{e,k})\} \cdot t$ 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; θ_i 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.

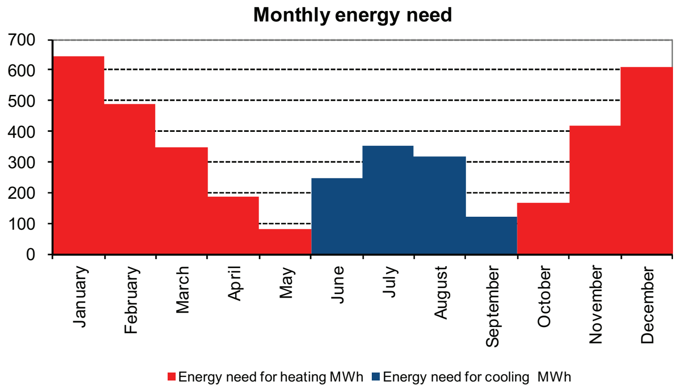

Fig. 2. Monthly energy consumption for heating and cooling of a five-floor building.

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

$Q_{G,H} = Q_i + Q_S$ are the total heat sources for the heating mode.

Q_i is the sum of internal heat sources over the given time period; $Q_i = \sum Q_{i,k} + \sum(1 - b_l)Q_{i,u,l}$ where $Q_{i,k}$ is the heat from internal heat source k in the conditioned zone during the month or season considered in MJ; $Q_{i,u,l}$ is the heat from an internal heat source l in an adjacent unconditioned space during the month or season considered in MJ; b_l is the reduction factor for the adjacent unconditioned space with internal heat source l, as defined in ISO/DIS 13789:2005.

Q_S is the sum of solar heat sources over the given time period; $Q_i = Q_{s,c} + \sum(1 - b_j)Q_{s,ujl}$ where $Q_{s,c}$ is the sum of solar heat sources during the month or season considered in the conditioned zone in MJ; $Q_{s,u,j}$ 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 $Q_{s,u,j}$, as defined in ISO/DIS 13789:2005.

$\eta_{G,H}$ 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:

$$Q_{NC} = Q_{G,C} - \eta_{L,C} \cdot Q_{L,C}$$

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

Q_{NC} is the building energy required for cooling in MJ;

Table 2
Primary energy in Spain in 2005 [14].

Floor number	Energy consumption in Spain (%)	(kg CO_2/MJ)	(g CO_2/kW h)
Coal	15.30	0.096	346.67
Oil	52.20	0.073	263.96
Natural gas	13.00	0.056	200.94
Nuclear energy	12.80	0.000	0.00
Renewable energy	6.70	0.000	0.00

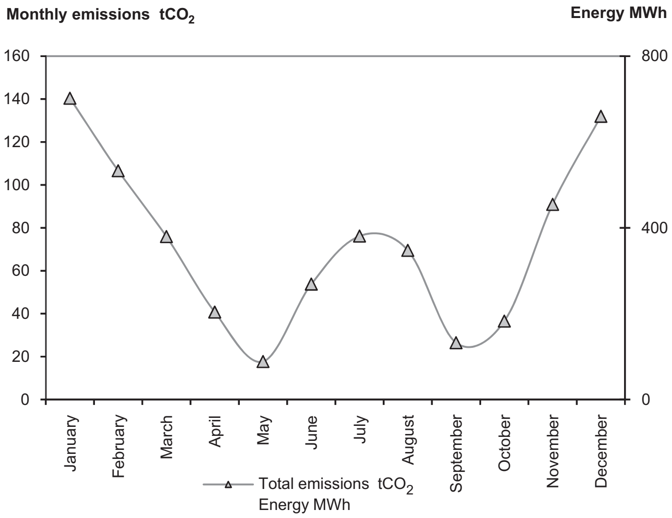

Fig. 3. Annual energy consumption of a building of 5 floors.

$Q_{L,C} = Q_T + Q_V$ is the total heat transfer for the cooling mode, determined in MJ;
$Q_{G,C} = Q_i + Q_s$ is the total heat sources for the cooling mode, determined in MJ;
$\eta_{L,C}$ is the dimensionless utilization factor for heat losses.

Once the initial conditions were established, the method outlined in the ISO standard was applied. This gave us the energy per month needed to maintain the building at the reference temperatures in winter as well as in summer. The following graph shows the monthly consumption throughout the year of a 60-floor building with a constructed surface of 75 000 m^2.

It should be underlined that the simplified method used in our study regarded the building as a monozone. 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 estimated CO_2 is a hypothetical value obtained from the distribution of the energy mix and emission factors, depending on the energy source used, according to the criteria of other authors [13]. Table 2 shows the values used to estimate the mean coefficient of emissions per kW h consumed. The distribution of primary energy consumption in Spain is shown in Table 2.

Based on these data, the CO_2 emissions in grams to generate a kW h come to a total of 216.95 g CO_2/kW h. This value was then used to obtain the emissions produced in the heating and cooling of the building. With this same value, it was also possible to estimate the emissions from the building construction materials, based on the energy needed to manufacture them. Fig. 3 shows the variation in building energy consumption, required to maintain set temperatures throughout the year. It also shows the CO_2 emissions in Tn, based on the previously mentioned coefficient.

When the calculations were repeated for each of the buildings, the results reflected the variation in energy consumption and the CO_2 emissions, depending on the number of building floors.

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.

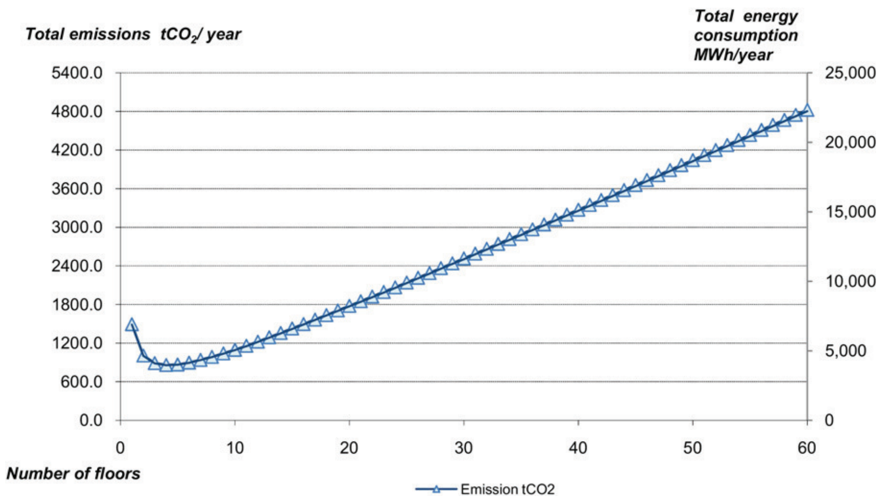

Fig. 4. Emissions in tonnes CO_2/year from heating and cooling (building surface 75 000 m^2).

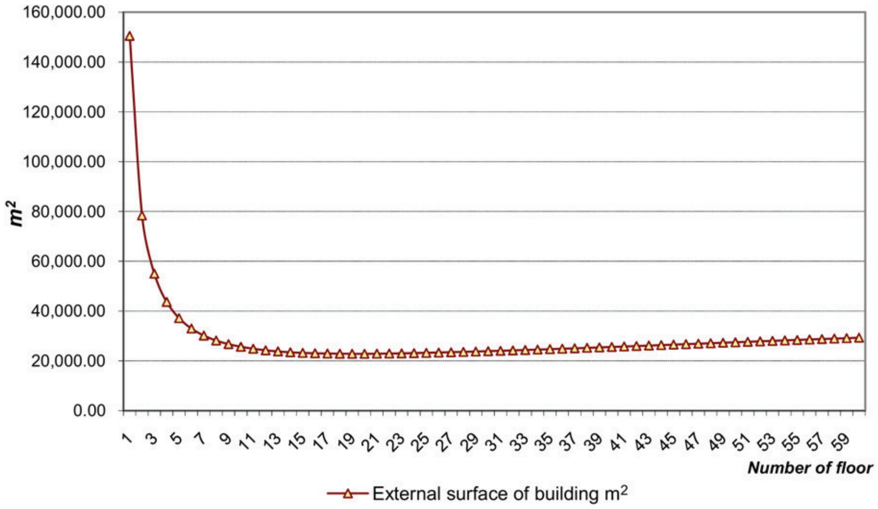

Fig. 5. External surface of the building, roof, and flooring in contact with the ground, depending on the number of floors.

$$K = \begin{pmatrix} \frac{E\cdot A_x}{L} & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{12\cdot E\cdot I_Z}{L^3} & 0 & 0 & 0 & \frac{-6\cdot E\cdot I_Z}{L^2} \\ 0 & 0 & \frac{12\cdot E\cdot I_Y}{L^3} & 0 & \frac{6\cdot E\cdot I_Y}{L^2} & 0 \\ 0 & 0 & 0 & \frac{G\cdot I_X}{L} & 0 & 0 \\ 0 & 0 & \frac{6\cdot E\cdot I_Y}{L^2} & 0 & \frac{4\cdot E\cdot I_Y}{L} & 0 \\ 0 & \frac{-6\cdot E\cdot I_Z}{L^2} & 0 & 0 & 0 & \frac{4\cdot E\cdot I_Z}{L} \end{pmatrix}$$

Where:

A is the profile section;
E is the longitudinal deformation modulus;
I_i is the inertia modulus in reference to the axis i ($i = x, y, z$);
$G = E/2\cdot(1+\upsilon)$ is the transversal deformation modulus and υ 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 m^2 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.

• Gravity load floor	4.7 kN/m^2
• Gravity load roof	6.2 kN/m^2
• Live load	3.0 kN/m^2
• Wind velocity	27 m/s
• Snow	1.0 kN/m^2

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 m^2 was also calculated for each of the following units: concrete (strength 25 kN/m^2; 30 kN/m^2; 40 kN/m^2; 50 kN/m^2); 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/CO_2 generated during the manufacturing process of each construction element [16].

These values were used to obtain the CO_2 emissions from the different items or building construction units: m^3 of concrete slabs,

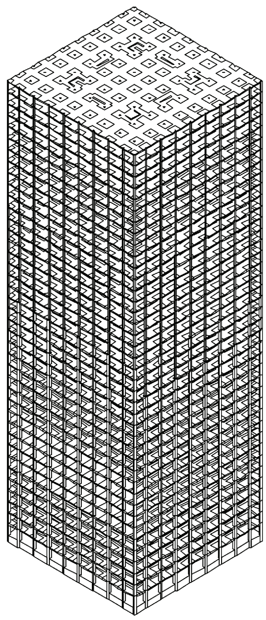

Fig. 6. Model for the calculation of the frame: Building of 40 floors.

Please cite this article in press as: Ordóñez J, Modi V, Optimizing CO_2 emissions from heating and cooling and from the materials used in residential buildings, depending on their geometric characteristics, Building and Environment (2011), doi:10.1016/j.buildenv.2011.04.030

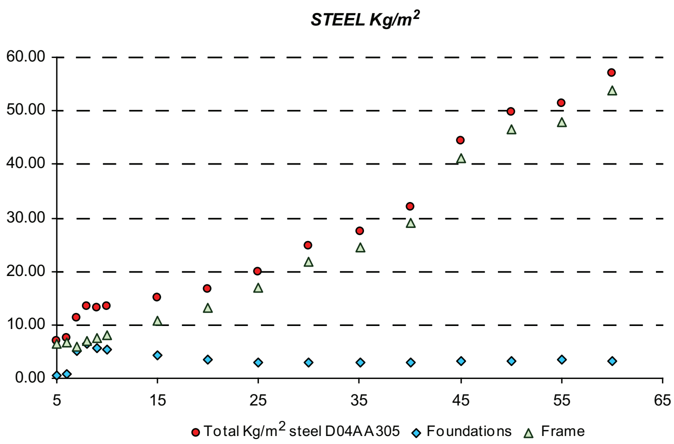

Fig. 7. Quantity of steel in the foundations and frame (kg/m^2).

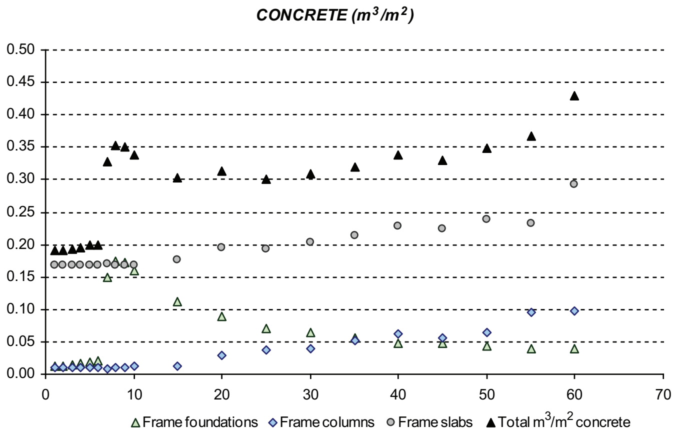

Fig. 8. Quantity of concrete in the foundation, frame and total (m^3/m^2).

m^2 of the envelope, kg of steel in the foundation, etc. It was also taken into account that each building unit might be composed of various materials. For example, 1 kg of steel used in the building means 1.03 kg of structural steel (the additional 3% is because of losses and overlaps) and 0.1 kg of wire to reinforce it (Table 4).

These data give the total emission in kg CO_2/m^2 due to the materials used in the construction of the building, and which vary

Table 4
Emissions due to elements used in the manufacturing process of units in the frame, envelope, and roof.

Unit		kg CO_2/un
kg	Steel b 500-s	2.202
m^3	Concrete HA-30/b/40/IIa	156.529
m^3	Concrete HA-40/b/40/IIa Slab	196.014
m^2	Work formwork on columns	0.298
m^2	Work formwork on slabs	0.489
m^2	Brick envelope 1/2 ft + air chamber + brick envelope 1/2 ft	40.846
m^2	Plaster	1.978
m^2	Projected polyurethane $d = 50$ kg/m^3	5.126
m^2	Plastic paint	1.229
m^2	Aluminium window	25.874
m^2	Glass 4 mm + air chamber 10 mm + glass 4 mm	18.007
M^2	Roof	29.200
m^2	Polystyrene insulation	5.010

in this case, depending on the number of floors. The elements studied were the foundation, frame, envelopes, and roofs (Fig. 9).

The result is the optimal value for the case analyzed and the starting conditions. The value obtained minimizes the environmental impact, measured in CO_2 emissions, of the construction materials used in a five-floor building.

6. Results

In accordance with our initial hypotheses and in the case of CO_2 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.

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 m^3 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

Table 3
Emissions due to elements used in the construction of building frames, envelops, and roofs.

Name	Density (kg/m^3)	Embodied energy (MJ/kg)	Carbon data (kg CO_2/kg)	ud	Carbon data (kg CO_2/ud)
Steel	7850.00	35.30	2.13	kg	2.13
Concrete	2340.00	1.11	0.07	m^3	156.53
Mortar (1:6)	1650.00	0.99	0.06	m^3	98.44
Mortar (1:3)	1650.00	1.40	0.08	m^3	139.21
Cement	1880.00	4.60	0.28	t.	277.21
Wood (pine)	510.00	5.42	–	M^3	0.00
Baked clay	850.00	3.00	0.18	mud	274.31
Sand	1800.00	1.00	0.06	m^3	108.47
Plaster	1200.00	1.80	0.11	M^3	130.17
PVC	1380.00	77.20	4.65	Ml	0.51
Expanded polystyrene	24.00	88.60	5.34	M^2	5.13
Aluminium	2700.00	155.00	9.34	M^2	25.87
Glass	2490.00	15.00	0.90	M^2	18.01
Paint		20.4 MJ/m^2		M^2	1.23
Polyester		80.50	4.85	M^2	0.73
Bitumen	2400.00	47.00	2.83	M^2	11.33
Bitumen	2400.00	47.00	2.83	M^2	13.60
Polypropylene		80.50	4.85	M^2	0.97
Expanded polystyrene	24.00	86.60	5.22	M^2	5.01

Source: Inventory of carbon energy (ICE) [16].

Please cite this article in press as: Ordóñez J, Modi V, Optimizing CO_2 emissions from heating and cooling and from the materials used in residential buildings, depending on their geometric characteristics, Building and Environment (2011), doi:10.1016/j.buildenv.2011.04.030

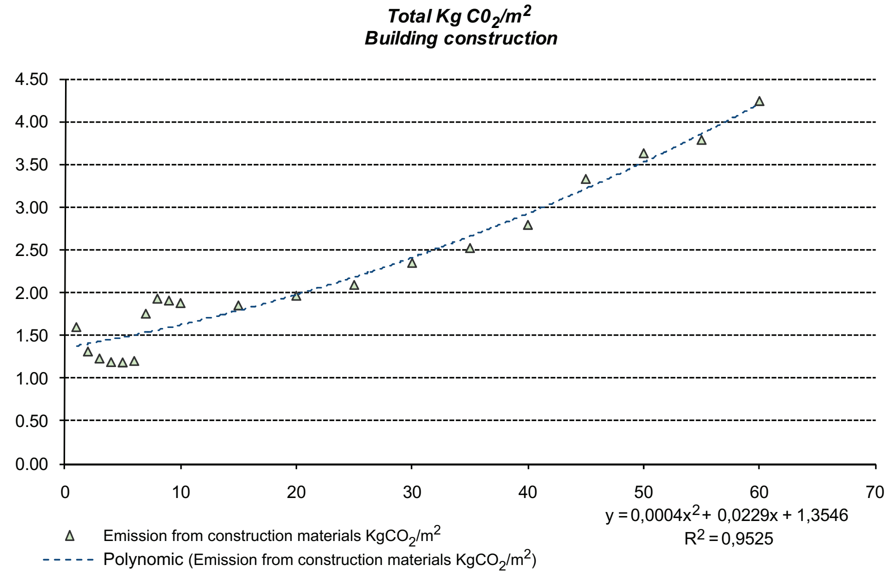

Fig. 9. Emissions due to construction materials (kg CO_2/m^2).

environmental impact for two factors studied, measured in CO_2 emissions, was found to be minimal for buildings of 4, 5, and 6 floors (see Fig. 10). As previously mentioned, the weight of the CO_2 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 CO_2 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 CO_2 emissions from building construction materials are very slight.

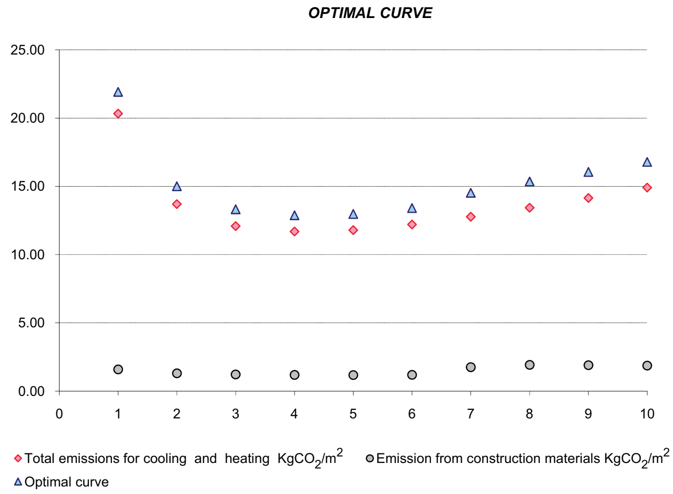

Fig. 11. Emissions in kg CO_2/m^2 for building floor height from 1 to 10. $T = 50$ years.

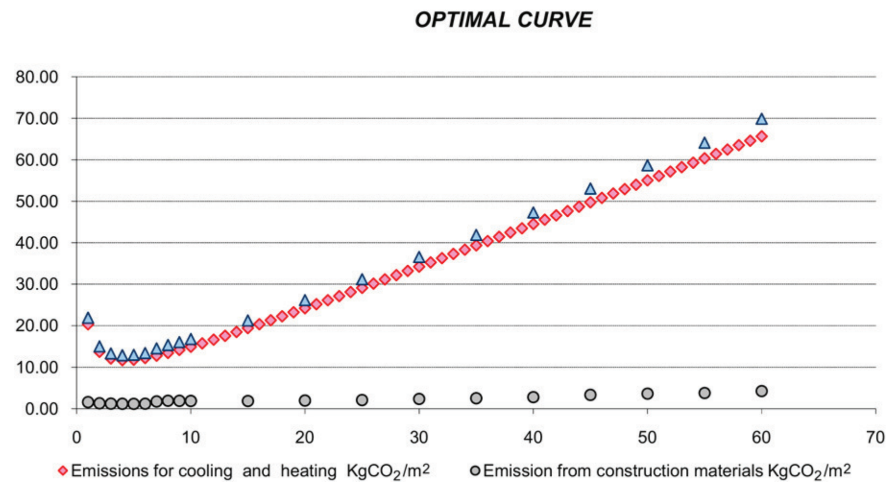

Fig. 10. Partial and total CO_2 emissions.

Please cite this article in press as: Ordóñez J, Modi V, Optimizing CO_2 emissions from heating and cooling and from the materials used in residential buildings, depending on their geometric characteristics, Building and Environment (2011), doi:10.1016/j.buildenv.2011.04.030

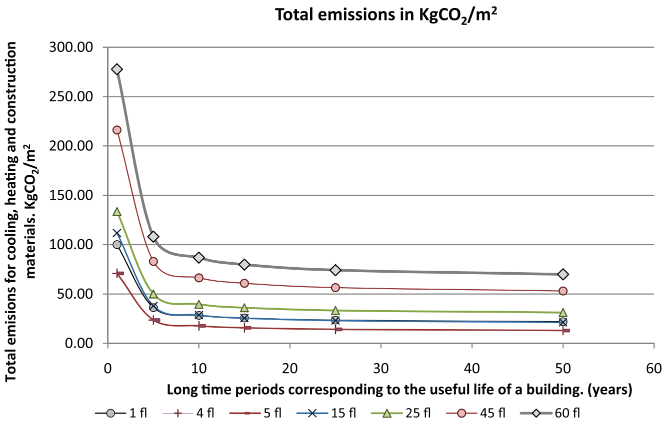

Fig. 12. Emissions in kg CO_2/m^2 in terms of the useful life of the building.

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. CO_2 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 CO_2 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.

References

[1] Dincer I. Renewable energy and sustainable development: a crucial review. Renew Sustain Energy Rev 2000;4:157–75.
[2] González M, García J. Assessment of the decrease of CO_2 emissions in the construction field through the selection of materials: practical case study of three houses of low environmental impact. Renew Sustain Energy Rev 2006;41:902–9.
[3] Depecker P, Menezo C, Virgone J, Lepers S. Design of building shape and energetic consumption. Build Environ J 2001;36:627–35.
[4] AlAnzi Adnan, Seo Donghyun, Krarti Moncef. Impact of building shape on thermal performance of office buildings in Kuwait. Build Environ J 2009;50:822–8.
[5] Chel Arvind, Tiwari GN. Thermal performance and embodied energy analysis of a passive house – case study of vault roof mud-house in India. Appl Energy 2009;86:1956–69.
[6] Chel Arvind, Tiwari GN. Performance evaluation and life cycle cost analysis of earth to air heat exchanger integrated with adobe building for New Delhi composite climate. Energy Build 2009;41:56–66.
[7] Omer AM. Energy, environment and sustainable development. Renew Sustain Energy Rev 2008;12:2265–300.
[8] Omer AM. Renewable building energy systems and passive human comfort solutions. Renew Sustain Energy Rev 2008;12:1562–87.
[9] Resolucion exenta no43 del 26 de diciembre del 2002 materia: fija vida útil normal a los bienes físicos del activo inmovilizado para los efectos de su depreciación, conforme a las normas del no 5 del artículo 31 de la Ley de la Renta, contenida en el articulo 10 del d.l. no 824, de 1974.
[10] Council on Tall Building and Urban Habitat. http://buildingdb.ctbuh.org.
[11] Documento Básico SE-AE Seguridad Estructural. Acciones en la Edificación. Madrid: Ministerio de Fomento; 2006.
[12] ISO/DIS 13790. Thermal performance of buildings — calculation of energy use for space heating and cooling. International Organization for Standardization; 2005.
[13] González M, García J. Assement of the decrease of CO_2 emissions in the construction field through the selection of materials: practical study of three houses of low environment impact. Build Environ J 2006;41:902–9.
[14] Instituto para la Diversificación y Ahorro de Energía (IDEA). Bulletin n° 8. October 2006.
[15] http://www.cype.es/.
[16] Hammond G, Jones C. Inventory of carbon energy (ICE). University of Bath; 2008.

Please cite this article in press as: Ordóñez J, Modi V, Optimizing CO_2 emissions from heating and cooling and from the materials used in residential buildings, depending on their geometric characteristics, Building and Environment (2011), doi:10.1016/j.buildenv.2011.04.030