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Application of Compromise Programming to a semi-detached housing development in order to balance economic and environmental criteria

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Abstract

European Energy Performance of Buildings Directives 2002/91/EC and 2010/31/UE promote energy efficiency in buildings. Under these Directives, the European Union States must apply minimum requirements regarding the energy performance of buildings and ensure the certification of their energy performance. The Directives set only the basic principles and requirements, leaving a significant amount of room for the Member States to establish their specific mechanisms, numeric requirements and ways to implement them, taking into account local conditions. With respect to the Spanish case, the search for buildings that are more energy efficient results in a conflict between users' economic objectives and society's environmental objectives. In this paper, Compromise Programming is applied to help in the decision-making process. An appropriate distribution of types of dwellings, according to their energy performance and to the climatic zone considered in Spain, will be suggested. Results provide a compromise solution between both objectives.

Keywords: Building, Optimization, Energy, Environmental Studies, Compromise Programming.

1. Introduction

Improving energy efficiency in buildings is considered a useful measure to decrease carbon emissions. This aspect is taken into account by the *Energy Performance of Buildings Directive* (EPBD) 2002/91/EC, recently updated by Directive 2010/31/UE. These regulations must be transposed by the EU member states to adapt them to their own particular conditions (climatic features, national regulations, building procedures, etc.) (Rey *et al*, 2007; Andaloro *et al*, 2010). In Spain, the EPBD was partially transposed by means of three royal decrees:

- Royal Decree approving the Technical Building Code (CTE), approved by the Council of Ministers on 17th March 2006 and published in the Official Gazette on 28th March 2006. One of the ‘basic documents’ of the CTE, entitled CTE-HE, deals with energy saving. The requirements regarding energy performance in buildings in this document are in line with those set out in the EPBD in terms of energy saving and renewable energy systems. As of 17th September 2006, these requirements became mandatory for new buildings and buildings undergoing major renovations.

- Royal Decree on the Basic Procedure for Energy Performance Certification of new buildings (RD 47/2007), approved by the Council of Ministers on 17th January 2007, and published in the Official Gazette on 31st January 2007. Certification became compulsory for new buildings when applications for building permits were made after 31st October 2007.

- Royal Decree approving the review of the current ‘Regulations for Thermal Installations in Buildings (RITE)’, approved by the Council of Ministers on 20th July 2007 and published in the Official Gazette on 29th August 2007. RITE came into force on 1st March 2008.

The EPBD was partially transposed in Spain because the energy performance certification of existing buildings is not covered by the new decrees. Certification of existing buildings is still awaiting administrative approval.

These regulations can become an important means of ensuring sustainable development in the building sector, by means of the energy performance. However, it is possible that the better the energy performance is (meaning lower social cost), the higher the private cost will be (including depreciation, maintenance and energy consumption). This does in fact happen, as can be seen from the results of the analysis in section 3. As a consequence, it is impossible to minimize the two objectives together, that is to say, the economic objective, with the lowest private cost, and the environmental objective, achieved by decreasing the carbon emissions. The carbon emissions of the building can be measured using the energy performance of the building.

The aim of this paper is to obtain the optimum combination for a semi-detached housing development, bearing in mind the two objectives mentioned above. It therefore seeks to achieve a feasible combination of dwellings with different energy performances (considering a new building development) that meets the objective of minimizing both private and social costs. This will be performed for every climatic zone in Spain, using Compromise Programming.

This paper is divided into five sections, besides this introduction, which reflect the process that was followed:

The second section describes the particular conditions in Spain, so that they can be taken into account in the analysis. On the one hand, this includes a definition of the specific procedures used to obtain the energy performance and, on the other hand, the climatic zones that can be found throughout Spain. The third section will describe the sources of information used to obtain private costs and the carbon emissions released during the use of the building. The methodology will be explained in the fourth section, where the generalities of Compromise Programming will be discussed. Results of the application of Compromise Programming to dwellings will be shown in the fifth section, taking into account the data that were calculated in the third section. Finally, the main conclusions will be explained in the sixth section. A discussion about the current and foreseen situation in Spain will also be included.

2. Problem statement within the Spanish conditions

As a consequence of the Spanish regulations based on the European EPBD, buildings must carry an energy efficiency label as a measure of their aptitude in energy efficiency, using a grade system made up of letters from A to G, A being the most efficient and G the least, as shown in Figure 1.

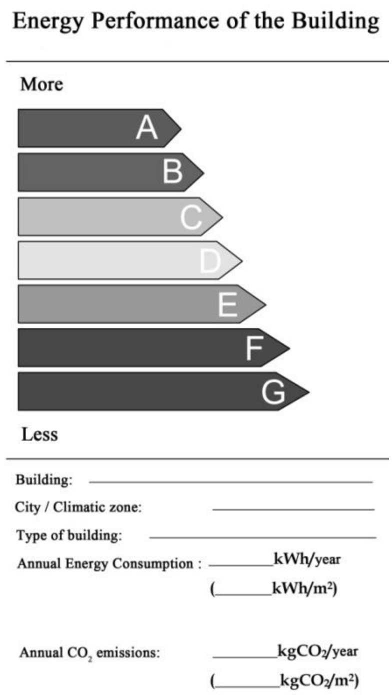

Figure 1. Energy Efficiency Label. Source: RD 47/2007

New buildings can be graded using five values, which are labelled using the letters A to E. Existing buildings can adopt lower grades such as F and G, but since new buildings must comply with CTE requirements, they will always be grade E or higher.

Considering the EPDB, these values can be defined according to limit values for two types of indicators: Kg CO_2 emissions per year and Primary Energy Consumption per year, in kWh. The Directive does not specify whether one or both indicators must be used to define the energy performance. In fact, there are differences among the European Members when it comes to using one indicator or the other (Concerted Action EPBD, 2008). In the case of Spain, the two types of indicators have been considered in the methodology defined for energy efficiency labelling "*Escala de calificación energética. Edificios de nueva construcción*" [Energy rating scale. New buildings] (AICIA, 2009), which was developed by the Thermotechnics Group of the School of Industrial Engineers of the University of Seville for the Spanish Ministry of Industry, Tourism and Trade's Institute for Energy Diversification and Saving (IDAE).

According to the CTE, there are two ways to obtain energy performance: the simplified option and the general option. Several methodologies have been officially approved (by the Ministry) for applying the simplified option (CE2, CES, CERMA, etc.). However, the simplified option can only be used provided that the building meets the minimum requirements, basically regarding the area of windows, which are not met in this case. Moreover, simplified options do not allow an energy performance above D (i.e. C, B or A) to be obtained. To date, Calener-VYP is the only official tool for the general option that has been accepted by the Spanish Ministry of Industry, Tourism and Trade. This software calculates the two indicators mentioned earlier, depending on the type of dwelling (house or multi-storey building), the climatic zone where the building is located, and the minimum contribution of solar energy for domestic hot water. However, although both indicators are calculated by the tool, only the limits of the indicator Kg CO_2 emissions per year are used to obtain the energy performance.

According to the CTE, there are 12 climatic zones in Spain, which are defined depending on the energy demand of buildings, as shown in Table 1.

SEVERITY OF SUMMER	SEVERITY OF WINTER Min.				Max.
	A	B	C	D	E
Min. 1			**C1**	**D1**	**E1**
2			**C2**	**D2**	
3	**A3**	**B3**	**C3**	**D3**	
Max. 4	**A4**	**B4**	**C4**		

Table 1. Climatic zones. Source: produced by the authors based on the CTE

This nomenclature consists of a letter and a number, depending on the severity of the winter and the summer, respectively. The letter A indicates the mildest winter, while E means the harshest. Number 1 corresponds to the coolest summer, whereas number 4 refers to the hottest. The grey cells in Table 1 represent non-existent combinations. The Figure 2 presents the distribution of the climatic zones, considering the capital of each Spanish province. Cities in a province could belong to different climatic zones as it also depends on their altitude (appendix D1, CTE-HE1).

Figure 2. Distribution of the climatic zones, represented by the capital of the Spanish provinces. Source: produced by the authors based on the CTE

The limits of the CO_2 emissions to determine the energy performance of the building differ among the climatic zones. For each zone a representative city has been selected (Table 2)

Climatic Zone	Selected cities	Minimum solar contribution for DHW	Energy Efficiency Performance (Kg CO_2/m^2/year)				
			A	B	C	D	E
A3	Málaga	60%	<4.6	4.6-8.9	8.9-14.9	14.9-24.0	>24.0
A4	Almería	70%	<4.4	4.4-8.3	8.3-14.0	14.0-22.6	>22.6
B3	Castellón	60%	<5.4	5.4-10.4	10.4-17.4	17.4-28	>28.0
B4	Sevilla	70%	<6.3	6.3-11	11.0-17.9	17.9-28.1	>28.1
C1	Santander	30%	<7.8	7.8-12.7	12.7-19.8	19.8-30.4	>30.4
C2	Barcelona	30%	<7.9	7.9-13	13.0-20.2	20.2-31.0	>31.0
C3	Granada	60%	<8.2	8.2-14	14.4-23.2	23.2-36.6	>36.6
C4	Badajoz	70%	<7.0	7-12.4	12.4-20.0	20.0-31.5	>31.5
D1	Pamplona	30%	<13.2	13.2-20.2	20.2-30.2	30.2-45.2	>45.2
D2	Logroño	50%	<10.9	10.9-17.8	17.8-27.8	27.8-42.6	>42.6
D3	Madrid	60%	<10.0	10-16.4	16.4-25.4	25.4-39.1	>39.1
E1	Burgos	30%	<16.9	16.9-25.9	25.9-38.7	38.7-57.9	>57.9

Table 2. Limit values for the indicator Kg CO_2/m^2/year (for single-family buildings) Source: produced by the authors based on the AICIA 2009 methodology

Although only 30% of residential buildings in Spain are single-family houses (Spanish National Statistics Institute, 2001 census housing), in this paper a semi-detached house was analyzed.

Besides the availability of data of an actual semi-detached houses development, single-family houses are easier to simulate using Calener VYP and they are considered more inefficient regarding to energy consumption (usually bigger areas, more façades and windows, etc.)

3. Information sources

The building used as a model to obtain private costs and emissions data is a semi-detached house with a basement floor used as a garage and utility room and ground and upper floors for residential use. It has an area of 68.10 sq metres on the ground floor and 58.88 sq metres on the first floor.

3.1. CO_2 emissions

The official Spanish software consists of two different tools: Lider v.01 is used to check that the minimum values for energy demand are reached (CTE requirements), and Calener VYP is used, in the case of residential buildings, to determine the energy performance (by means of the energy efficiency label) and the carbon emissions as Kg CO_2, as explained in the previous section. There are 60 possible combinations resulting from the five energy performance grades (A-E) and the 12 climatic zones. Only 50 combinations could be obtained because sometimes performance E was not reached after implementing the commercial format of constructive solutions and sometimes performance B could not be achieved with the materials and facilities used in this study.

3.2. Private costs

Three components are considered: depreciation, maintenance and energy consumption costs, in €/m^2/year:

$$C = C_{DE} + C_{MAN} + C_{EN} \quad [1]$$

where,

C: total private costs

C_{DE}: depreciation cost

C_{MAN}: maintenance cost

C_{EN}: energy consumption cost

3.2.1. Depreciation cost for the building and periodic renewal of its elements

First of all, investment costs for the 50 combinations "energy performance-climatic zone" are calculated by drawing up an estimation or budget with the minimum constructive solutions that fulfil the energy demand requirements in accordance with the CTE. Several solutions are used depending on the energy performance: different insulation thicknesses, types of glass and window profiles, various heating or air-conditioning systems, etc. To achieve this, measurements are taken from the plans of the building and entered on measurement sheets. These data are then transferred to specially ruled sheets that have a rate column ready for pricing. Prices are adapted to each Spanish province by means of the database for construction prices Cype S.A.

To estimate the depreciation cost from the investment cost, the service life of the different elements that go to make up the building are considered. This cost allows estimating the cost per year. The service life for the whole building is considered to be 100 years, as confirmed in various sources (Rudbeck, 2002; Johnstone, 2001a, 2001b; Davies and Wyatt, 2004; Article 19 ECO 805/2003). This fits the observed ages of buildings from the Spanish building stock, according to data from the Spanish National Statistics Institute.

The service life for facilities and materials, which is shorter than that of the building considered as a whole, ranges from 10 to 25 years (Liska, 2000; Llano, 2007). Fifteen years is the time adopted for facilities and 25 years for constructive elements such as tiles, kitchen utilities, and so forth. A linear depreciation is going to be considered, with a null residual value.

3.2.2. Maintenance cost

This cost is calculated in accordance with different authors (Piper, 1995; Brown, 1996; Liska, 2000; Kaiser, 2001; Brathal and Langemo, 2004) and prestigious institutions in the building sector, such as the Catalonian Technological Institute (ITEC, 1991a, 1991b, 1991c, 1991d, 1994, 1996, 1997, 1999). The *Libro del Edificio* (Building Log Book) was also reviewed. This is a document drafted when a building is constructed and it contains, among other things, several aspects regarding the management of the building during its operational phase. There are certain regulations, which vary slightly from one province to another, that also deal with this aspect (Decree 35/01, Balearic Islands; Decree 38/2004, La Rioja; Decree 158/1997, Catalonia; Decree 322/2000, Navarre; Decree 349/1999, Community of Madrid). Measurements and prices for each task were also taken into account, together with the periodicity with which they will occur during the service life of the building. Finally, 45 tasks were considered.

3.2.3. Energy consumption cost

Three types of energy sources were considered: electricity, natural gas and biomass. The official rates set by from the Spanish Government for electricity and natural gas were used, neither of them including Value Added Tax. There is no official data for biomass fuel, so this information was obtained from several suppliers and includes transport costs.

Table 3 shows the results for private costs (*C*), in €/m^2/year, and for CO_2 emissions (CO_2), according to the output of Calener VYP, in KgCO_2/m^2/year as shown in equation [1]:

Zone	Performance A					Performance B					Performance C					Performance D					Performance E				
	C_{DE}	C_{MAN}	C_{EN}	C	CO_2	C_{DE}	C_{MAN}	C_{EN}	C	CO_2	C_{DE}	C_{MAN}	C_{EN}	C	CO_2	C_{DE}	C_{MAN}	C_{EN}	C	CO_2	C_{DE}	C_{MAN}	C_{EN}	C	CO_2
A3	14.25	9.82	2.03	26.10	4.30	13.22	10.10	2.28	25.60	7.00	11.78	9.88	2.50	24.16	14.60	10.37	9.01	2.95	22.33	23.30					
A4	14.26	10.83	2.35	27.44	4.30	13.64	10.70	2.21	26.55	7.90	11.87	10.00	2.43	24.30	14.00	10.45	9.07	2.86	22.38	22.50					
B3	14.23	9.70	2.57	26.50	5.40	13.82	9.70	2.57	26.09	6.00	11.94	9.97	2.73	24.64	16.70	10.52	9.04	3.37	22.93	27.50					
B4	14.29	10.00	3.22	27.51	6.20	13.85	9.89	2.56	26.30	10.00	12.00	10.20	2.78	24.98	17.50	10.54	9.62	3.39	23.55	27.70	10.53	9.20	3.43	23.16	28.20
C1	14.06	11.97	2.35	28.38	4.50	12.81	12.29	2.32	27.42	12.70	12.50	12.26	3.08	27.84	19.50	12.16	11.72	3.37	27.25	22.20	10.94	10.83	3.97	25.74	33.50
C2	14.60	11.56	3.04	29.20	4.50	13.03	11.88	2.31	27.22	12.70	12.76	11.85	3.12	27.73	20.10	12.04	11.31	3,34	26.69	21.90	11.44	10.47	3.86	25.77	32.30
C3	13.39	11.38	3.37	24.80	7.00						11.21	11.70	3.40	28.49	22.90	10.05	11.11	4.22	26.52	36.20					
C4	11.58	10.13	2.41	24.12	6.50						11.12	10.34	3.08	24.54	20.00	9.94	9.88	3.73	23.55	31.10					
D1	14.11	13.45	4.26	31.82	3.10	12.41	13.84	3.06	29.31	19.40	11.98	13.82	4.06	29.86	28.60	9.23	13.14	5.10	27.47	44.90	9.22	12.25	5.21	26.68	46.00
D2	13.70	12.92	3.92	30.54	4.50	12.40	13.29	2.88	28.57	17.80	11.96	13.27	3.96	29.19	27.70	10.96	12.63	4.88	28.47	42.60	10.23	11.74	4.97	26.94	43.60
D3	14.67	12.43	3.65	30.75	5.90						12.81	12.70	3.66	29.17	25.20	11.53	11.15	4.38	27.06	37.60					
E1	13.47	11.52	4.63	29.62	2.00	12.11	11.85	3.65	27.61	24.70	11.60	11.82	4.45	27.87	32.10	10.29	10.55	5.79	26.63	51.80					

Table 3. Values obtained for CO_2 emissions ($KgCO_2/m^2$/year) and private costs (€/m^2/year) in every combination of climatic zone and energy performance

Usually, the better the energy performance is, the higher C and the lower the CO_2 component will be. In a few cases it is the other way round and this is because there is an important energy saving that offsets higher depreciation and maintenance costs.

4. Methodology

4.1. The efficient set

Multiple Criteria Decision Making, or MCDM, is applied when there are several conflicting criteria, that is, several criteria that matter but cannot be optimized at the same time. It is often used when environmental criteria are considered, usually in opposition to economic criteria. It has also been applied in areas like agricultural and forestry land planning (Berbel-Vecino, 1992), forestry management (Díaz-Balteiro and Romero, 1997**;** Díaz-Balteiro and Romero, 2003; Díaz-Balteiro and Rodríguez, 2006); or electric management (Linares and Romero, 2000). Recently, it has been applied to construction, for valuing sustainable industrial buildings (San José *et al*, 2007), or to the design of low-emission dwellings (Hamdy *et al*, 2011).

Within different multicriteria approaches, when the decision-maker makes his or her decisions in the context of multiple objectives, the multicriteria approach to be considered is Multiobjective Programming, or MOP. The aim is to obtain a set of efficient solutions, whose elements are attainable solutions, such that there is no solution with the same or better result for all the objectives being strictly better for at least one objective. There are four approaches to generating an efficient package: the weights method, constraints method, NISE (Non Inferior Set Estimation) and Multicriteria simplex. In this case the constraints method is used.

In the search for the set of efficient solutions with two conflicting objectives, one economic or private and other environmental or public, each reflecting the interests of the two agents involved, i.e. the one that generates pollution (home user) and the one that suffers it (society in general), the problem can be formulated in the following way:

For all i / i = A, B, C, D (E has not be considered because it could not be reached in most of the cases. Moreover, result of limits of CO_2 for E energy performance are very close to D, Table 3)

xi: percentage of housing type i

The set of efficient solutions that meet the two objectives will satisfy:

$Eff\ Z(x) = [Z_1(x), Z_2(x)]$

$Z_1(x)$: objective to minimize private cost

$Z_2(x)$: objective to minimize CO_2 emissions

Subject to F, defined by the set of constraints:

$xi \geq 0.1$, indicates a minimum of 10% of dwellings per energy performance category

$xi \leq 0.5$, indicates a maximum of 50% of dwellings per energy performance category

$\sum xi = 1$

These constraints were set in order to ensure that every energy performance A, B, C and D is representative (at least 10%) and that none of them prevail over the others (maximum of 50%). This could be set in a different way, but it is the hypothesis held by the authors of this paper. The formulation of the problem is different for each climatic zone. This is because buildings require different constructive solutions to fulfil the CTE requirements, depending on the climatic features of the building site, and also because differences in prices among the selected cities has been considered. The initial hypotheses are that there are no restrictions as regards budget, or CO_2 emissions.

The problem is solved by optimizing each objective separately. The minimization of $Z_1 (x)$ will result in a high percentage of dwellings that are cheaper in terms of depreciation, energy consumption and maintenance but which are, on the other hand, worse from an environmental point of view. In contrast, minimizing $Z_2 (x)$ will result in a high percentage of housing that is more expensive in terms of private costs, but better from an environmental point of view.

The optimal value of each objective is called ideal value and both ideal values altogether form the ideal point, which is represented by the vector (Z^*_1, Z^*_2). Obviously, this ideal point is unattainable because otherwise it would indicate that there is no conflict between the objectives. In consequence, there would be no problem of multicriteria choice and the ideal alternative would be the optimal solution.

The worst values of each of the two objectives, called anti-ideal values, make up the anti-ideal point, represented by the vector (Z_{1*}, Z_{2*}).

For each zone, the pay-off matrix, consisting of the anti-ideal and ideal values, is drawn up in order to quantify the level of conflict between the different objectives. A set of Pareto optimal solutions or the efficient set between the ideal and non-ideal values is obtained, thus yielding two subsets: the subset of efficient solutions and the subset of dominated or inferior solutions, which was produced without taking into account the preferences of the decision-maker.

The production frontier, transformation curve or efficient set which separates the inaccessible and accessible points is expressed as $T\ (Z_1,\ Z_2) = K$ and it is derived from the intermediate values between the ideal and anti-ideal by applying linear regression, which results in an approximation to the efficient set rather than an exact representation. Without losing generality, in this work all the criteria are minimized.

4.2. Compromise programming

The optimal private cost-carbon emissions product mix would be given by the point of tangency of the transformation curve $T\ (Z_1, Z_2) = K$ with the family of iso-utility curves $u\ (Z_1, Z_2) = \delta$ (see Figure 3). The problem is that these social utility curves are unknown and it would be necessary to rely on surveys of the population to obtain it, which would be very costly.

This problem can be solved by implementing the compromise approach proposed by Zeleny (1973, 1974), in which the point or mix of the transformation curve nearest to the ideal point for a general metric π will be considered an optimum solution. This proximity is measured by means of the mathematical concept of distance.

There are different compromise functions, depending on the metric that is chosen. Generally, the concept of distance between x^1 and x^2 is represented by the expression:

$$L_\pi = \left[\sum_{j=1}^{n} \left| x_j^1 - x_j^2 \right|^\pi \right]^{1/\pi} \qquad [2]$$

Depending on the value of π there are different distances, the most common of which are:

$\pi = 1$: Manhattan distance or L_1 norm

$\pi = 2$: Euclidian distance or L_2 norm

$\pi = \infty$: Chebyshev distance or L_∞ norm

Yu (1973) introduced the idea that all the solutions to equation [2] for all values of π between 1 and infinity define a subset of the efficient set $T\ (Z_1,\ Z_2) = K$ called a compromise set. Moreover, in bi-criteria problems, and under some conditions, the compromise set is bounded by the solutions for $\pi = 1$ and $\pi = \infty$ and it contains the best solutions, which are those that optimize both objectives altogether.

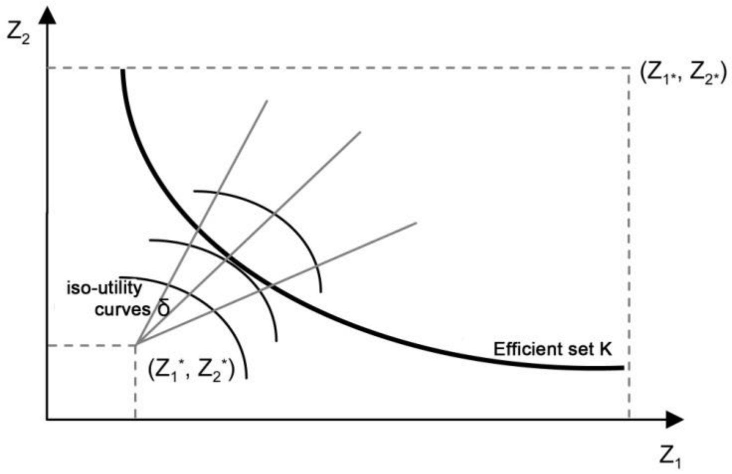

Figure 3. Social utility curve and distance between the ideal point and the efficient set

This has been used in various fields and countries, such as in land planning in Australia (Baja *et al*, 2007) or in management of the use of drinking water in Iran (Fattahi and Fayyaz, 2010) or even in non-environmental conflicts, such as economic growth and the rate of inflation in Spain (André *et al*, 2008). More specifically and very recently, in the construction sector, there is a proposal developed by Diakaki et al (2010) to choose the building materials. They use two goals which are minimizing material cost and transmittance for a particular building in Greece. Since we are facing a bi-criteria problem, this is going to be used in the application case.

Once the efficient set has been obtained and the inferior solutions have been removed, the next step in the decisional process will be to introduce the decision-maker's preferences or weights in order to reach the best solution. The weights are unknown, since they depend on the decision-maker's personal preferences. Therefore, some values are going to be adopted. One reasonable possibility is to assume that $W_1 = W_2$, which means that both objectives are equally important. Other arbitrarily adopted values will be $(W_1 = 2W_2)$ and $(W_2 = 2W_2)$ and a sensibility analysis will be performed with three pairs of values adopted for the weights W_1 and W_2. If distances are normalized and homogenized, and the decision-maker's preferences or weights are represented by W_j for each objective, the efficient solution will be found by solving equation [3]:

$$MinL_{\pi} = \left[\sum_{j=1}^{2} W_j^{\pi} \left| \frac{Z_j^* - Z_j(x)}{Z_j^* - Z_{*j}} \right|^{\pi} \right]^{1/\pi} , \qquad subject\ to\ x \in F \qquad [3]$$

For metric $\pi = 1$, equation [3] is:

$$MinL_1 = \sum_{j=1}^{2} W_j \frac{Z_j^* - Z_j(x)}{Z_j^* - Z_{*j}} = \sum_{j=1}^{2} W_j \frac{Z_j(x) - Z_j^*}{Z_{*j} - Z_j^*} \qquad [4]$$

in the case of ideal values below the anti-ideal values:

$$MinL_1 = \sum_{j=1}^{2} W_j \frac{Z_j(x)}{Z_{*j} - Z_j^*} = \sum_{j=1}^{2} \alpha_j Z_j(x) \qquad [5]$$

where the constant α_j represents the normalized weight, defined as $\alpha_j = W_j/(Z^*_j - Z_{*j})$

For metric $\pi = \infty$, it minimizes the maximum deviation among all the individual deviations, as only the greatest diversion influences the process of minimization. The minimization problem is resolved in this case:

Min L = d, subject to X Є F

$$\alpha_1 \left[Z_1^* - Z_1(x) \right] \leq d$$

$$\alpha_2 \left[Z_2^* - Z_2(x) \right] \leq d \qquad [6]$$

From equation [5] it can be inferred that solution L_1 corresponds to a position that minimizes the weighted sum of the achievements of each objective, which can be interpreted as a point of maximum efficiency.

As demonstrated by Ballestero and Romero (1991), the solution L_{∞} satisfies the following relationship between both objectives:

$$W_1 \frac{Z_1^* - Z_1(x)}{Z_1^* - Z_{*1}} = W_2 \frac{Z_2^* - Z_2(x)}{Z_2^* - Z_{*2}} \quad [7]$$

If distances are weighted *(Wj)* and standardized $(1/(Z^*_j - Z_{*j}))$ between the value achieved by each objective, this indicates that it is a choice that strikes a balance among the various objectives, which is not the case with solution L_1, as shown in equation [7], and considering that $\alpha_j = W_j/(Z^*_j - Z_{*j})$:

$$\alpha_1 \left[Z_1^* - Z_1(x)\right] = \alpha_2 \left[Z_2^* - Z_2(x)\right] \quad [8]$$

In addition, in the case of a bi-criteria utility function, the necessary and sufficient condition to be able to take advantage of the fact that the solution that maximizes the utility function belongs to the efficient set for any transformation curve is that the marginal rate of substitution between $Z_1(x)$ and $Z_2(x)$ K is equal to $\alpha 1/\alpha 2$, as shown in equation [9]:

$$\frac{Z_1^* - Z_1(x)}{Z_2^* - Z_2(x)} = \frac{\alpha_1}{\alpha_2} = K \quad [9]$$

However, since the transformation curves are an approximation to the efficient set, it might be the case that some points satisfying the $T(Z_1, Z_2) = K$ equation are not really efficient and some of them might be even unfeasible. Therefore, the points are going to be determined using the equations [5] and [6].

5. Results

The ideal and anti-ideal points that are obtained, taking into account every objective and every climatic zone, are summarized in Table 4. It also contains the transformation curves, obtained using the linear regression considering values in-between the ideal and anti-ideal values:

Zone	Economic Objective		Environmental Objective		Transformation curve or efficient set approximation
	Z_1^*	Z_{1*}	Z_2^*	Z_{2*}	$T(Z_1,Z_2)$
A3	23.57	25.37	8.04	17.16	$Z_1 = 27.034 - 0.21 *Z_2 + 0.000493 * Z_2^2$
A4	23.87	26.35	8.17	16.67	$Z_1 = 29.811 - 0.49 *Z_2 + 0.008048 * Z^2$
B3	24.11	25.87	8.92	19.90	$Z_1 = 27.664 - 0.23 *Z_2 + 0.002713* Z_2^2$
B4	24.17	26.18	12.44	23.01	$Z_1 = 29.803 - 0.36 *Z_2 + 0.004886* Z_2^2$

C1	26.69	27.79	11.26	24.26	$Z_1 = 28.882 – 0.1063 *Z_2 + 0.000642* Z_2^2$
C2	26.64	28.06	12.22	24.26	$Z_1 = 31.455 – 0.38 *Z_2 + 0.007383* Z_2^2$
C3	26.03	27.13	16.28	27.96	$Z_1 = 29.083 – 0.14 *Z_2 + 0.000919* Z_2^2$
C4	23.88	24.23	14.37	20.02	$Z_1 = 27.455 – 0.34 *Z_2 + 0.008031* Z_2^2$
D1	27.93	30.23	17.38	37.09	$Z_1 = 33.736 – 0.25 *Z_2 + 0.002432* Z_2^2$
D2	28.00	29.51	17.13	35.25	$Z_1 = 33.293 – 0.29 *Z_2 + 0.004124* Z_2^2$
D3	28.27	29.75	16.79	29.47	$Z_1 = 34.138 – 0.35 *Z_2 + 0.004995* Z_2^2$
E1	28.10	28.60	19.59	27.22	$Z_1 = 30.892 – 0.16 *Z_2 + 0.001991* Z_2^2$

Table 4. Ideal and anti-ideal points per objective and transformation curve in each climatic zone

Table 5 summarizes the results for metrics L_1 and L_∞, in agreement with equations [5] and [6], and the percentages per type of dwelling that are obtained, as regards their energy performance. There are three columns for the optimum combination of economic and environmental objectives, which correspond to the different weights adopted, as can be seen in the first row in Table 5. Results show that the higher the weight assigned to the economic objective W_1 is, the lower the value Z_1 will be, which implies a higher percentage of poorer energy performances. On the other hand, the higher the weight for the environmental objective is, the lower the value Z_2 will be, meaning a higher percentage of better energy performances. However, Z_2 values range between wider limits than Z_1 values when different weights are adopted. Regarding the metrics that were applied, L_1 and L_∞, it can be said from the results that, when using the L_∞ metric, the percentage of homes with better qualifications increases because it provides a more balanced choice than the L_1 metric.

Weights		$W_1 = 2W_2$						$W_1 = W_2$						$2W_1 = W_2$					
Climatic Zone	Metric	(Z_1, Z_2)	X_A	X_B	X_C	X_D	X_E	(Z_1, Z_2)	X_A	X_B	X_C	X_D	X_E	(Z_1, Z_2)	X_A	X_B	X_C	X_D	X_E
A3	L_1	(23.58, 17.16)	10	10	30	50		(23.97, 15.10)	30	10	10	50		(25.38, 8.04)	50	30	10	10	
	L_∞	(24.17, 14.10)	18	10	50	22		(24.47, 12.59)	43	10	10	37		(24.77, 11.04)	50	11	10	29	
A4	L_1	(23.88, 16.67)	10	10	30	50		(25.28, 11.33)	30	10	50	10		(26.35, 8.17)	50	30	10	10	
	L_∞	(24.67, 13.56)	18	10	50	22		(25.04, 12.18)	25	10	50	15		(25.43, 10.84)	35	10	45	10	
B3	L_1	(24.11, 19.90)	10	10	30	50		(25.38, 11.30)	10	50	30	10		(25.75, 9.04)	30	50	10	10	
	L_∞	(24.67, 15.94)	10	38	10	42		(24.94, 14.11)	10	47	10	33		(25.21, 12.36)	10	50	20	20	
B4	L_1	(24.17, 23.01)	10	10	10	20	50	(25.57, 14.71)	10	50	20	10	10	(26.18, 12.44)	50	20	10	10	10
	L_∞	(24.80, 19.10)	10	10	47	10	23	(25.10, 17.35)	10	18	50	10	12	(25.40, 15.67)	10	37	33	10	10
C1	L_1	(26.70, 23.91)	10	20	10	10	50	(27.21, 17.67)	10	50	10	10	20	(27.76, 12.31)	50	20	10	10	10
	L_∞	(27.04, 19.65)	10	40	10	10	30	(27.22, 17.51)	11	50	10	10	19	(27.40, 15.48)	18	50	10	10	12
C2	L_1	(26.69, 23.34)	10	20	10	10	50	(27.22, 16.42)	10	50	10	20	10	(27.47, 14.68)	20	50	10	10	10
	L_∞	(27.02, 18.83)	10	43	10	10	27	(27.17, 16.86)	10	50	10	16	14	(27.37, 15.36)	16	50	10	14	10
C3	L_1	(25.86, 20.27)	50		10	40		(25.86, 20.27)	50		10	40		(26.45, 16.28)	50		40	10	
	L_∞	(26.13, 18.42)	50		24	26		(26.19, 18.00)	50		27	23		(26.26, 17.52)	50		31	19	
C4	L_1	(23.93, 17.69)	50		10	40		(23.93, 17.69)	50		10	40		(24.23, 14.36)	50		40	10	
	L_∞	(23.98, 17.20)	50		14	36		(24.03, 16.58)	50		20	30		(24.09, 15.91)	50		26	24	
D1	L_1	(27.93, 37.09)	10	10	10	20	50	(28.91, 26.56)	10	50	10	10	20	(30.17, 17.38)	50	20	10	10	10
	L_∞	(28.63, 29.36)	10	39	10	10	31	(28.95, 26.16)	11	50	10	10	19	(29.30, 23.26)	18	50	10	10	12
D2	L_1	(28.00, 32.84)	10	20	10	10	50	(28.49, 25.10)	10	50	10	10	20	(29.44, 17.20)	50	20	10	10	10
	L_∞	(28.40, 26.63)	10	44	10	10	26	(28.58, 24.12)	12	50	10	10	18	(28.79, 21.87)	18	50	10	10	12
D3	L_1	(28.27, 29.47)	10		40	50		(29.11, 20.51)	50		10	40		(29.75, 16.79)	50		40	10	
	L_∞	(28.61, 25.39)	31		19	50		(28.78, 23.39)	41		10	43		(28.99, 21.56)	47		10	43	
E1	L_1	(27.35, 36.72)	10	30	10	50		(28.14, 21.34)	30	50	10	10		(28.54, 16.80)	50	30	10	10	
	L_∞	(28.15, 21.21)	31	49	10	10		(28.18, 20.86)	32	48	10	10		(28.22, 20.48)	34	46	10	10	

Table 5. Compromise solutions for the metrics L_1 and L_∞ and percentages for each type of dwelling in terms of their energy performance

6. Conclusions and discussion

This paper reports an application of the Compromise Programming to obtain optimum economic and environmental values for a housing development in each climatic zone in Spain. On the one hand, the economic value is the result of combining depreciation, maintenance and energy consumption costs. On the other hand, the environmental value is determined through the energy efficiency of the building, which is measured using the carbon emissions of the house.

The optimum solution found will help the decision-maker when it comes to choosing the types of houses to build, according to their energy performance. Moreover, obtaining an optimum solution requires establishing the weight that must be given to each objective. The weights are unknown since they depend on the decision-maker's own preferences. Therefore, some values are going to be adopted by performing a sensibility analysis with three pairs of values adopted for the weights W_1 and W_2: $W_1 = W_2$, $W_1 = 2W_2$ and $2W_1 = W_2$.

Compromise Programming has made it possible to refine the set of efficient solutions, whose end points are defined by the metric $\pi = 1$ and $\pi = \infty$. As mentioned before, L_1 corresponds to a situation that maximizes the weighted sum of the achievements of each objective, which can be equivalent to a point of maximum efficiency. But on the other hand, in the metric L_∞, there is a more balanced choice between different objectives. Regarding the composition of housing according to its energy efficiency, when using the L_∞ metric, the percentage of homes with better qualifications increases because it provides a more balanced choice. This makes it more interesting than the L_1 metric, given the tendency that the market will predictably display, as governments increase protection of environmental values.

The present economic recession in Spain, which is hitting the building sector particularly hard, is responsible for the lack of new housing developments fulfilling the CTE requirements. Moreover, the frantic building activity that characterised the last few years just before the onset of the economic recession has resulted in an enormous stock of available houses, built under the old regulations, before the CTE. Therefore, buildings constructed according to CTE regulations are still not representative in the market. Nowadays, economic factors seem to prevail over environmental ones, so it seems that developers are more likely to focus on their economic convenience. But this situation will probably be changing in the short-medium term. The EU

Members must fulfil their commitments to reach the Kyoto targets, and so governments will have to implement mechanisms to promote the decrease in CO_2 emissions. In fact, the recent Directive 2010-31/EU indicates that the Member States shall ensure that by 31st December 2020, at the latest, all new buildings must be near zero energy consumption. This suggests that the situation will change in order to encourage increasingly better energy ratings. Therefore, from the developer's point of view, it will be interesting to opt for solutions where environmental aspects prevail.

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