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A mathematical model for the sustainability of the use of cross-laminated timber in the construction industry: the case of Spain

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Abstract In recent years, computerized mathematical modelling has enabled construction-related problems to be resolved and predictions to be made regarding the behaviours of buildings and their environments in a more rigorous fashion than was the case with the deterministic models used until now. This model enables the analysis of a simulation of the sustainability of the use of timber as a major structural component in construction. Thus, using a unique model, which could be adapted to the particular characteristics of any country, the viability of a sustainable use of woodland can be verified, with extraction rates below 100 %, in order to supply an industry which accounts for a high percentage of the carbon dioxide emissions released into the atmosphere. In the specific case of Spain, the demographic forecasts for the next 40 years were used as the basis on which to establish the operational period of the model. For this period, the different variables involved in the natural production of wood were compared, along with felling strategies. The results point to sustainable scenarios for the most part during the target period in Spain, with the most unfavourable combinations of the variables preventing the sustainability of the use of timber from being achieved.

Keywords Mathematical modelling · Sustainability · Cross-laminated · Timber · Construction

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Introduction

The situation with regard to energy and CO_2 emissions

Current research estimates that energy demand will increase by 40 % over the next 20 years, mainly in developing countries. The reasons behind this increase are continued population growth, the movement of manufacturing to Asian countries, and the emergence of a growing middle class in the region. However, the distribution of this demand currently remains uneven and stable, affordable, efficient and environmentally friendly energy systems need to be developed. The politicians and the energy industry must address the three horns of the 'trilemma' of energy security, social equity and environmental impact mitigation (Policies for the future 2012).

Despite this huge expected demand, progress towards a sustainable energy policy is scarce. With regard to pollution, the maximum levels established in the Kyoto Protocol for greenhouse gas emissions have clearly been exceeded by most industrialised countries over the last few years (Sikdar 2009). Moreover, a large proportion of these emissions has been made by the construction industry (Yeheyis et al. 2013). In addition to the life cycle analysis, is necessary to supplement with other valuation methods that provide a more complete picture of sustainability (Bare 2013). Therefore, the detailed study of a model which carefully and comprehensively examines the sustainability of the transformation of forests into building materials seems both logical and necessary, as a substantial reduction in emissions could be achieved in this way (Cabezas et al. 2003).

Timber as a sustainable alternative

The aim of this study is to make a mathematical instrument available to society which can assess the sustainability of timber production. Consideration is also given to how such production may be able to provide sufficient material to absorb the total demand of the whole construction industry, as well as meet overall demand within the timber industry for a given country.

Cross-laminated timber panels are used for the structure and envelope of new buildings. Such panels can also provide energy savings during their life cycle of some 35 %, along with a 97 % reduction in CO_2 emissions, when compared with traditional reinforced concrete frames and steel structures. Other research also points to an immediate reduction in emissions and energy consumption by using renewable materials such as timber or straw-bale panels (Milutiene et al. 2012).

Mathematical modelling

To correctly calculate the system, it is necessary to develop more comprehensive models that include additional ways to analyse risks and benefits of the proposal (Ingwersen et al. 2013). In order to perform a rigorous calculation of the problem, mathematical modelling was employed, using iterations of the system for the calculation period. In order to justify the viability of the proposal, it was necessary to demonstrate the sustainability of the use of timber as a large-scale construction material for building structures and envelopes. Finally, different scenarios and strategies were considered, taking the rates of natural growth of forests and of the demolition of homes as the key variables for the process. The extraction rate was the strategy variable used, in order to maintain the sustainability of the construction and timber industries. There are two basic objectives for the present model:

1. To analyse the sustainability of the large scale use of cross-laminated coniferous timber in construction. The first step was to undertake an analysis of wood growth in Spanish forests, taking into account those elements which positively or negatively impact upon natural growth, and the causes and factors affecting reforestation for erosion control. The rest of the model attempts to determine the possible demand for timber in the whole construction industry. To do this, a diagram with five levels was drawn up which takes population growth and a complete property market system for the whole country into account. Timber production and felling for the purposes described make up the rest of the model.
2. To propose two scenarios for the sustainable exploitation of tree-covered areas. The first scenario uses the current extraction rate, while the second goes somewhat further in order to attempt to establish not only the demand of the construction industry but also what would be necessary for the whole timber industry, so that imports would not be required.

Table 1 List of abbreviations used

Symbol	Description
VOB	Volume over bark
salmt	Wolfram Mathematica programming language—provides results in a matrix of variable *mt*
Abs	Wolfram Mathematica programming language—returns a positive result of the variable
data	Wolfram Mathematica programming language—provides results in a matrix of variable mt
i	Indicates the value of the timber stocks for each year in question
T	Indicates the complete period under study
N	Wolfram Mathematica programming language—ensures a result is obtained in the range of natural numbers
Sum	Wolfram Mathematica programming language—sum data
mexpm	Enables the calculation of the variance of the experimental data
mmodm	Enables the calculation of the variance of the data obtained from the model
R2m	Formula for calculating the coefficient of determination and reveals the functional dependency between the experimental data and the mathematical model
INE	National Statistical Institute

Thus, the level variable *mte* (timber produced for construction) is what will indicate whether the model is sustainable or not. In order for it to ensure sustainability, it must meet the potential demand from the industry and use woodland resources in a sustainable fashion.

A list of the abbreviations used in the paper is provided in Table 1.

Materials and methodology

Programming the model, variables and equations

In order to make a rigorous calculation of the problem, a computerised validation was carried out due to the large number of equations to solve. Specifically, the calculation programme we used was *Wolfram Mathematica* (Universitat Politècnica de València 2012). A Forrester diagram is shown below illustrating the complete model, along with the variables it is comprised of (Fig. 1a–c).

Different scenarios and strategies have been considered. The variables chosen for the formulation stage of the experiments were *tcn* (natural growth rate) and *tdd* (home demolition rate). The *tap* variable (coniferous wood usage rate in construction) was the strategy variable used, in order to ensure the sustainability of the timber and construction sectors.

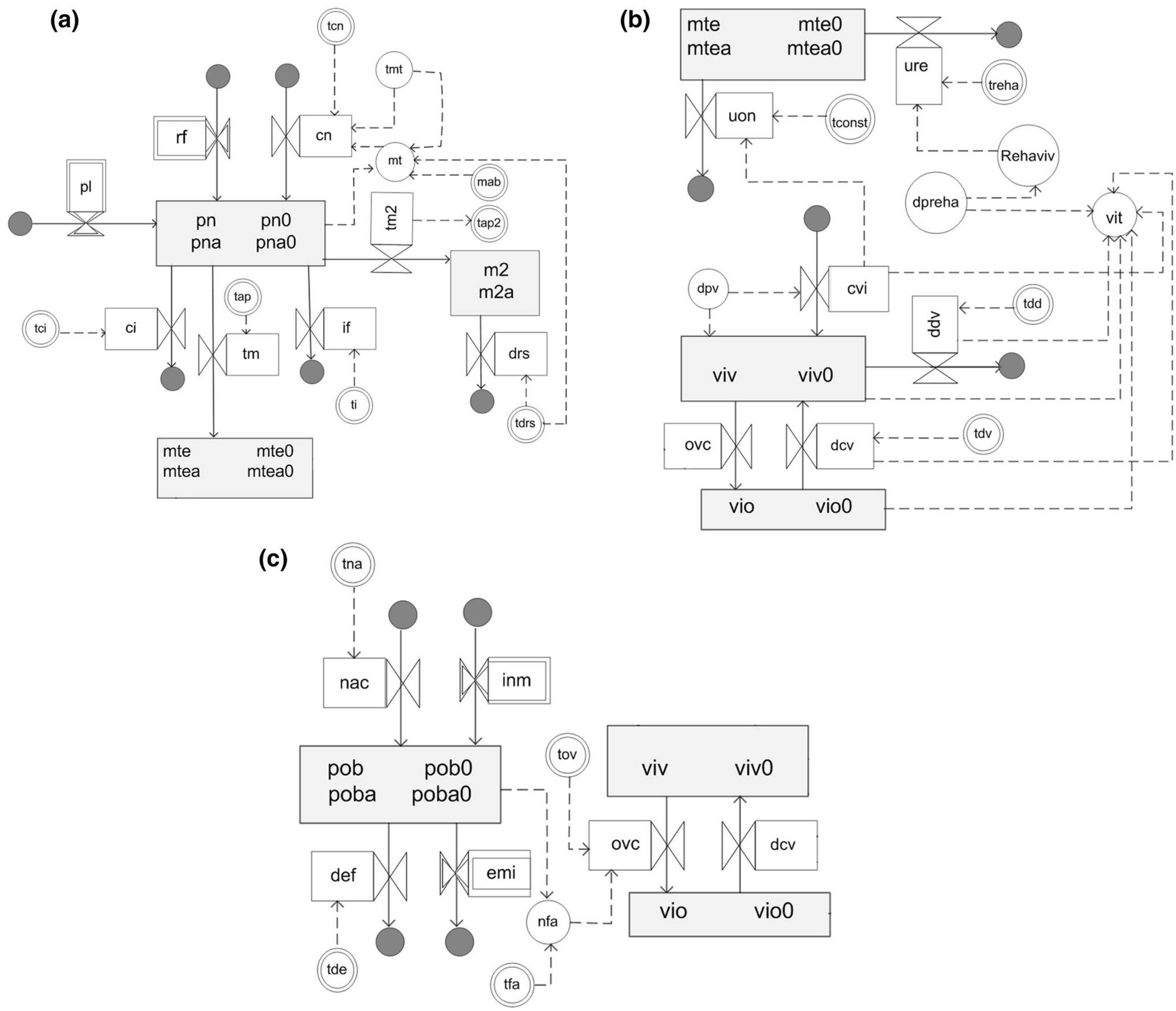

Fig. 1 **a** Forrester diagram. Interaction between wood production in forests and felling for the purpose of extracting coniferous timber for structural or other uses. **b** Construction industry draws on the stock of harvested coniferous timber for structural use. **c** Demand for home occupancy by the population

Building on this, the first strategy could be formulated, involving using all of the coniferous timber currently extracted for use as structural materials in housing in Spain. The extraction rate currently stands at 41.38 %, which is very low in comparison with other EU countries (Situation of forests 2010). This timber represents approximately 48.61 % of the annual regeneration of VOB (volume over bark) in the country. Along with these two coefficients, it is also important to note that only 36 % is used to produce sawn timber for the manufacture of cross-laminated timber boards (Situation of forests 2010).

The second strategy, however, went somewhat further, as it aimed at extracting not only sufficient material to meet the demand from the construction industry but also for that of the whole timber industry in Spain. This strategy thus included the demand for paper, wood pulp, timber products for the furniture industry, particle board, meaning that no timber would need to be imported from outside Spain.

Mathematical models of timber production can be classified into several types (Dieguez Aranda 2009), based on a range of criteria:

- The prediction units used and the level of detail involved: stand-based models, classification by species, age or size, individual tree.
- Their evolution over time: static or dynamic models.
- The randomness of the model inputs: deterministic and stochastic models.

Table 2 Variables used in the mathematical model

Variable	Description	Units
ci	Illegal felling	m^3 VOB
cn	Natural growth	m^3 VOB
cvi	Construction of homes	Homes
dcv	Home vacancy	Homes
ddv	Demolition of homes	Homes
def	Deaths	People
dpreha	Positive demand for rehabilitation	
dpv	Positive demand for homes	
drs	Consumption by the rest of the wood and paper market	m^3 VOB
emi	Emigration	People
if	Forest fires	m^3 VOB
inm	Immigration	People
m2	Timber produced for other uses	m^3 VOB
m2a	Annual timber produced for other uses	m^3 VOB
mab	Current wood in forests	m^3 VOB
mt	Total timber = mab + pn	m^3 VOB
mte	Timber produced for construction	m^3 VOB
mtea	Annual timber produced for construction	m^3 VOB
nac	Births	People
nfa	Number of families	Families
ovc	Occupancy of constructed homes	Homes
pl	Planting	m^3 VOB
pn	Natural wood growth	m^3 VOB
pna	Annual natural wood growth	m^3 VOB
pob	Population	People
poba	Annual population	People
rehaviv	Rehabilitation of homes	
rf	Reforestation	m^3 VOB
tap	Coniferous wood usage rate in construction	
tap2	Usage rate for other purposes in the timber industry	
tci	Illegal felling rate	
tcn	Natural growth rate	
tconst	Construction rate	
tdd	Home demolition rate	
tde	Death rate	
tdrs	Rate of demand in the rest of the market	
tdv	Home vacancy rate	
tfa	Number of families rate	
ti	Fire rate	
tm	Felled coniferous timber	m^3 VOB
tm2	Felling for other purposes	m^3 VOB
tmt	Total timber rate	
tna	Birth rate	
tov	Home occupancy rate	
treha	Rehabilitation rate	
uon	Use in new-build homes	m^3 VOB
ure	Use of timber for the rehabilitation of homes	m^3 VOB
vio	Occupied homes	Homes
vit	Total homes = vio + viv	Homes
viv	Vacant homes	Homes

– How growth is forecast: empirical models, process-based models and hybrid models.

According to this classification, the proposed model for the forestry simulation is stand-based, static, deterministic and hybrid.

Variables

The variables used in the mathematical model are shown in Table 2.

Values used in the programming of the different variables

The initial values of the variables used in the mathematical model are shown in Table 3.

Equations

The equations used in the mathematical model are shown in Table 4.

Validation

In order to validate the model with historical data, the period chosen for comparison was that of 1980–2009. Thus, the following calculations were taken into account:

– VOB reserves in 1980 in tree-covered areas—488,114,662 m^3 VOB (National Forestry Inventory 2005).
– Annual growth of wood volume 1980—31,025,000 m^3 VOB, 6.35 % of existing reserves (National Forestry Inventory 2005).

The validation results are shown in Fig. 2, which compares the timber stock predicted by the model with the real stock in these years.

Calculation of the relative error

The relative error was calculated using the following mathematical expression.

$$\mathrm{Table}[\{\mathrm{salmt}[[i,1]], 100 * \mathrm{Abs}[\mathrm{data}[[i,2]] - \mathrm{salmt}[[i,2]]] / \mathrm{data}\,[[i,2]]\}, \{i,1,T\}] // N \quad (32)$$

Table 3 Initial values used in the mathematical model

Variable	Value
t0	2009
dt	1
T	40
pl	12,918,080
rf	3,064,750
ti	0.1038
pn0	20,801,443
pna0	20,801,443
tcn	0.0325
mte0	0
mtea0	0
m20	0
m2a0	0
mab	927,761,315
tci	0.1135
tap	0.0724
tap2	0.3414
tdrs	0.3348
tna	0.00832
inm	386,466
emi	324,203
tde	0.0085
tfa	2.74
tconst	38.55
treha	25.55
tov	3.31
tdv	0.00005
tdd	0.000758
pob0	45,828,172
poba0	0
viv0	2,525,000
vio0	22,525,917

Table 4 Equations used in the mathematical model

Equation	Number
$mt(t) = mab(t) + pn(t - dt)$	(1)
$tmt(t) = 0.005\colon mt(t) > 1\ 238\ 652\ 815$	(2)
$tmt(t) = 0.005\colon mt(t) \leq 1\ 238\ 652\ 815$	(3)
$cn(t) = mt(t) + dt\ *(tcn + tmt)$	(4)
$ci(t) = tci * (cn + pl + rf)\ (t - dt)$	(5)
$tm(t) = tap * (cn + pl + rf)\ (t - dt)$	(6)
$tm2(t) = tap2 * (cn + pl + rf)\ (t - dt)$	(7)
$nac(t) = tna * pob\ (t - dt)$	(8)
$def(t) = tde * pob\ (t - dt)$	(9)
$nfa(t) = poba(t - dt)/tfa$	(10)
$ovc(t) = nfa(t) * tov$	(11)
$vit(t) = viv\ (t - dt) + vio\ (t - dt)$	(12)
$dcv(t) = tdv * vit\ (t)$	(13)
$ddv(t) = tdd * vit(t)$	(14)
$dpv(t) = 0.0044\text{: } viv(t - dt) < 500\ 000$	(15)
$dpv(t) = 0.00018\text{: } viv(t - dt) \geq 500\ 000$	(16)
$cvi(t) = dpv(t) * vit(t)$	(17)
$uon(t) = cvi(t) * tconst$	(18)
$dpreha(t) = 0.00002579 * (vit(t)/1\ 000\ 000)$	(19)
$rehaviv(t) = dpreha(t) * vit(t)$	(20)
$ure(t) = rehaviv(t) * treha$	(21)
$pn(t) = pn(t - dt) + dt * (cn(t) + rf(t) + pl(t) - ci(t) - tm(t) - tm2(t) - if(t))$	(22)
$pna(t) = pna0 + dt * (cn(t) + rf(t) + pl(t) - ci(t) - tm(t) - tm2(t) - if(t))$	(23)
$mte(t) = mte(t - dt) + dt * (tm(t) - uon(t) - ure(t))$	(24)
$mtea(t) = dt * (tm(t) - uon(t) - ure(t))$	(25)
$m2(t) = m2(t - dt) + dt * (tm2(t) - drs(t))$	(26)
$m2a(t) = dt * (tm2(t) - drs(t))$	(27)
$pob(t) = pob(t - dt) + dt * (nac(t) + inm(t) - def(t) - emi(t))$	(28)
$poba(t) = dt * (nac(t) - def(t) + inm(t) - emi(t))$	(29)
$viv(t) = viv(t - dt) + dt * (cvi(t) - ovc(t) + dcv(t) - ddv(t))$	(30)
$vio(t) = vio(t - dt) + dt * (ovc(t) - dcv(t))$	(31)

where the variable i indicates the value of the timber stocks for each year in question, and the variable N ensures a result is obtained in the range of natural numbers.

The errors produced per year specified are shown in Table 5.

Calculation of the coefficient of determination

The coefficient of determination was calculated in accordance with the following expressions, where the *mexpm* variable enabled the calculation of the variance of the experimental data, and *mmodm* enabled the calculation of the variance of the data obtained from the model. The *R2m* variable represents the formula for calculating the coefficient of determination and reveals the functional dependency between the experimental data and the mathematical model.

$$mexpm = \text{ Sum }[\text{data}[[i,2]],\{i,2,T\}]\,/\,(T-1)\,//N \quad (33)$$

$$mmodm = \text{ Sum }[\text{salmt}[[i,2]],\{i,2,T\}]\,/\,(T-1) \quad (34)$$

$$R2m = \text{Sum }[\text{salmt}[[i,2]] - mmodm) * (\text{data}[[i,2]] - mexpm), \{i,2,T\}]^2 / (\text{Sum }[\text{salmt}[[i,2]] - mmodm)^2, \{i,2,T\}]) * (\text{Sum }[\text{data}[[i,2]] - mexpm)^2, \{i,2,T\}]) \quad (35)$$

A value of 0.998179 was obtained, which is very close to 1, therefore, validating the model.

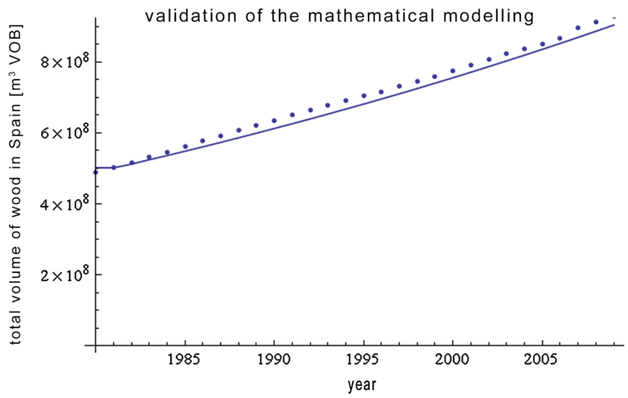

Fig. 2 Comparison between the wooden stock model with the real stock

Table 5 Relative error for the validation of the model

Year	Rel. Error
1980	2.80707
1986	2.80251
1992	3.63892
1998	2.73708
2004	2.0706
1981	0.0516906
1987	3.19304
1993	3.54799
1999	2.50216
2005	1.85992
1982	0.91943
1988	3.43005
1994	3.37756
2000	2.40296
2006	1.74104
1983	1.4263
1989	3.59882
1995	3.16066
2001	2.41418
2007	2.94779
1984	1.51764
1990	3.67218
1996	2.83499
2002	2.41091
2008	2.85246
1985	2.39712
1991	3.68521
1997	2.77306
2003	2.39026
2009	2.5451

Data from Wolfram Mathematica

Experimental design

Scenario variables

1. Home demolition rate (*tdd*)
2. Natural growth rate (*tcn*)

Control variables

1. Usage rate of timber for construction (*tap*).
2. Usage rate of timber for other uses (*tap2*).

Objective

For the timber for use in construction, *mte*, to always be above zero. The possible scenarios were the combination of a low or average production of resources over the last decade, together with a stable demolition rate or a moderately high one caused by a possible increase in demolition of buildings in a poor state.

Scenarios

E1 Low home demolition $tdd = 0.000758$, moderate natural growth of forests $tcn = 0.0325$.
E2 Low home demolition $tdd = 0.000758$, low natural growth of forests $tcn = 0.01625$.
E3 High home demolition $tdd = 0.001137$, moderate natural growth of forests $tcn = 0.0325$.
E4 High home demolition $tdd = 0.001137$, low natural growth of forests $tcn = 0.01625$.

Strategies

S1 current usage in Spain of timber, $tap = 0.0724$ and $tap2 = 0.3414$ (Situation of forests 2010).
S2 Usage of timber in order to satisfy the needs of the wood and paper industry, 70 % of the total annual growth, $tap = 0.1225$ and $tap2 = 0.5774$ (Situation of forests 2010).

Calculation

Demand for timber from the construction industry in Spain

Demand for new-build homes

First of all, the forecast for demographic growth made by the INE (National Statistical Institute) for Spain for the next 40 years was taken as the basis for the calculation of the demand for timber. In this forecast, the population steadily ages and, taking migration into account, the population is estimated to increase by 2,138,481 people over the whole period (Population Projection 2010).

This larger population chosen as our model for demographic behaviour would live in homes which were potentially available for occupation and was subject to the parameters estimated for the average household size established in the INE report. Their latest estimation, from 2007, established the average household size to be 2.74 people per home (Informative Bulletin 2009).

This demand for vacant homes had to be increased further due to the fact that 15 % of Spanish households possess a second home, according to the latest census of population and homes in 2001 (Informative Bulletin 2009).

To this demand for vacant homes per family, it was also necessary to add further demand in the form of the purchases of dwellings by foreign citizens who are not resident in Spain, taking the following parameters into account:

1. Due to the attractive prices in the current Spanish property market, a minimum demand was established for the future years of 16,480 homes per year (Table 6). This was the number recorded in 2009, largely for second homes (Property Statistics 2012).
2. 25,651 homes per year, an annual increase of 4.2 % (Table 6).

The potential annual housing demand is expressed in Table 6.

Housing market

The difficult first task consisted of establishing how many homes make up Spain's housing stock. The data from the 2001 census of population and homes was the initial starting point, and then the current housing stock was estimated using forecasts and official data from the INE (Construction Statistics 2009). Taking all these data into account, Table 7 was drawn up, which summarizes Spain's housing stock on 1st January 2009.

Finally, using INE data (Construction Statistics 2009), it was also necessary to establish the mean floor-space of homes in Spain, especially from 1997 onwards, when most of the current housing stock began to be built. Table 8 illustrates this, showing the weighted floor-space of homes in Spain.

Table 6 Projected demand for vacant homes in the 2009–2049 period

Type of approximate annual demand	Number of homes
Population increase	19,511
Increase due to possession of second homes	2,926
Foreign investment from non-residents in 2009	16,480
Predicted increase in average demand	25,651
Total annual demand	64,584

Having determined the overall housing stock, the next step was to establish the level of surplus housing stock. This variable is closely linked to the previous one, and it was one of the most difficult aspects to assess for this study.

The report published by the trade magazine *Observatorio Inmobiliario y de la Construcción* is that which best describes this phenomenon (Verges 2011), which includes the values shown in the graph below (Fig. 3). The data include stock according to status, but not land which is being held in reserve, due to a lack of data.

Therefore, the surplus housing stock on the 1st January 2009 numbered 2,525,000 homes, which can be broken down as shown in Table 9.

In order to calculate the demand for timber in new-build homes over the whole of the construction sector, the construction and geometric characteristics shown in Table 10 were assumed.

Table 7 Summary of current and planned housing stock

Item	Homes
Housing stock in January 2001	20,946,554
Homes built during January 2001–December 2008	4,104,363
Total housing stock	25,050,917
Homes planned January 2001–December 2008	4,861,582
Licences awarded January 2001–December 2008	4,498,633
Homes awaiting award of a licence	362,949
Homes awaiting completion of construction	394,270

Data from Instituto Nacional de Estadística

Table 8 Mean floor-space of homes in Spain in the 1997–2008 period

Concept	Number	%	Weighted result (m^{2})
Total detached houses	1,738,346	26	
Total apartments	4,914,780	74	
Total number of homes	6,653,126	100	
Mean floor-space for period			
House	155.88	m^2	40.73
Apartment	102.08	m^2	75.41
Total mean floor-space for the 1997–2008 period			116.14

Data from Instituto Nacional de Estadística

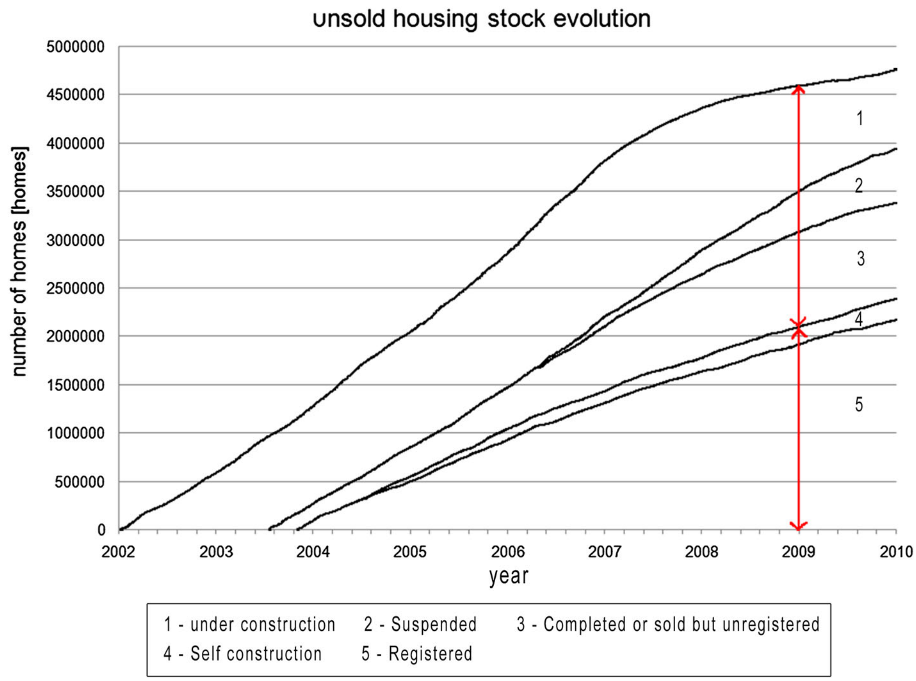

Fig. 3 Unsold housing stock evolution

Table 9 Total surplus housing stock generated since 2002

Item on 1st January 2009	Number of homes
Total surplus housing stock	2,525,000
Under construction	1,100,000
Suspended	450,000
Completed or sold but unregistered	975,000

Data from Observatorio inmobiliario y de la construcción

Table 10 Demand for timber per home

Calculation of the necessary volume for new-build homes	Measurement	Units
Mean floor-space of homes in Spain 1997–2008	116.14	m^2
Increase for envelope and partition walls	1.50	–
Mean thickness of replacement material	0.22	m
Mean volume of material/home	38.32	m^3 timber/home

Demand deriving from the rehabilitation of homes and demolitions

The final estimate regarding potential demand concerns that deriving from the rehabilitation of homes. For this purpose, it was necessary to estimate the future number of instances of structural rehabilitation and partial demolition. Several sources were used to gain information on a sector which is very difficult to quantify. Of all these sources, the tables published by the Ministerio de Fomento (Ministry of Public Works) regarding rehabilitation and demolition in the construction industry are those which offer the most detailed view of this activity (Construction Statistics 2012).

The model generated a demand from rehabilitation which is similar to that seen in 2008–2009, slightly higher than the mean average in the sector before the deflation of the property bubble and taking the view that it could be one of the areas of activity of greatest promise in the industry. The estimated number was 16,184 homes/year. For each instance of rehabilitation work referred to above, it was assumed that the need for timber for each rehabilitated home would be as shown in Table 11.

Finally, the instances of total demolition are a key factor in the reduction of vacant homes in the property market. These were included in the *tdd* variable. The variables included in the proposed model did not at all share the same level of impact. A very small variation in *tdd* would greatly modify the results obtained from the model. For this reason, it was chosen for the design of scenarios.

Timber production in Spain

Natural growth in Spanish forests

The analysis of the changes in the volume of timber stored in Spanish forests between 1975 and 2009 also enables a clear conclusion to be drawn: Spain's timber reserves are increasing. Thus, the timber contained in Spanish forests

Table 11 Demand for timber per rehabilitated home

Calculation of the necessary volume for rehabilitation	Measurement	Units
Mean floor-space of homes in Spain 1997–2008	116.14	m^2
Mean thickness of replacement material	0.22	m
Mean volume of the material/home	25.55	m^3 timber/home

has increased by 101.9 % in little more than 30 years, going from 456.70 million m^3 to 921.91 million m^3. Timber production in 2009 amounted to 46,136,000 m^3 VOB (Situation of forests 2010).

The growth of tree-covered area and of volume currently amounts to 5 % of the total. Of that percentage:

1. 6.65 % corresponds to reforestation.
2. 65.35 % corresponds to natural forest growth.
3. The remaining 28.00 % corresponds to human planting.

Timber industry, Coniferous production, Expectations

With a value of 41.3 %, Spain's use of this resource falls well below the level at which felling is sustainable. To this extraction rate, we applied a second coefficient which represents the percentage attributed to usage in construction, with 36 % destined for use as sawn timber and beams. The rest of the material is used for props and posts in mining, other industrial uses, particle board and fibreboard, for pulp manufacturing or for re-use as biomass (Situation of forests 2010).

For the simulation model employed in this study, the stock of harvested timber was taken to be zero, as a conservative measure.

The extraction rate of the proposed model maintains the usage seen in the current model for strategy 1. For this strategy, an extraction rate of 41.38 % = *tap* + *tap2* was used.

Finally, the illegal felling of trees for timber and firewood and use of products originating from the tree-covered forested area, by individuals for heating, hot water and cooking, can also be estimated as a constant for the calculation cycle in question. Thus, the following assumptions were made concerning the consumption of wood-based products originating from the tree-covered forested area by a significant number of Spanish families whose main place of residence is situated in rural areas, or in the rural–urban fringe, according to the INE (De la Riva et al. 2008):

1. Large-scale use for heating by 30 % of families.
2. A consumption of 5 m^3 VOB/year per family.

The extraction rate of the model was divided into two:

1. *tap* Equivalent to the annual extraction rate of coniferous timber for structural use. This was obtained by multiplying the extraction rate, 0.4138, the percentage of coniferous timber of the total grown annually 0.4861, and the percentage solely destined for sawmills 0.36 = 0.07242.
2. *tap2* Equivalent to the rest of the timber production for the rest of the industry. For an extraction rate of 0.4138, the tap2 value was 0.3414.

Quantification of the variables used. The case of the Spanish market

Having examined the information on timber production (Situation of forests 2010), the following statements can be made, which serve as the basis for the generation of the mathematical model.

The natural growth of forests depends on the climatic conditions and the total volume of timber, which produces a feedback effect on the system. At a certain volume of timber in Spanish forests, growth due to climatic conditions starts to occur. If this volume is not reached, the system suffers a slight penalization. This threshold can be found in the data emerging from reforestation for erosion control purposes in Spain (PNAP 2007).

Thus, the following are taken into account:

1. The area to reforest, practically the same as the current tree-covered area, is 18,400,000 ha.
2. 6,217,830 ha of these are considered to be a priority to reforest. This is the figure at which there would be a change in climatic conditions to ones which are more favourable for the generation of tree mass. This would lead to an increase in reserves of 310,891,500 m^3 VOB.

Thus, with the new volume of 927,761,315 + 310,891,500 = 1,238,652,815 m^3 VOB, natural growth is boosted by 0.5 % in volume. If this level is not reached, there is a penalizing effect of −0.015 % on volume (Situation of forests 2010). The mean average over the last 20 years lost to forest fires is 154,864 Ha/year, of which 38.50 % corresponds to tree-covered areas, which is 59,637 Ha/year, or 2,981,850 m^3 VOB (Forest fires in Spain 2010). Although the number of fires is of the same order of magnitude as in previous decades, the tree-covered area which is burnt is much lower. We assume that sufficient attention and resources will be employed in the future to maintain the performance currently achieved. The number of fires can be estimated and the annual burnt tree-covered area is a proportional value which varies according to the annual production of tree mass, as it makes a

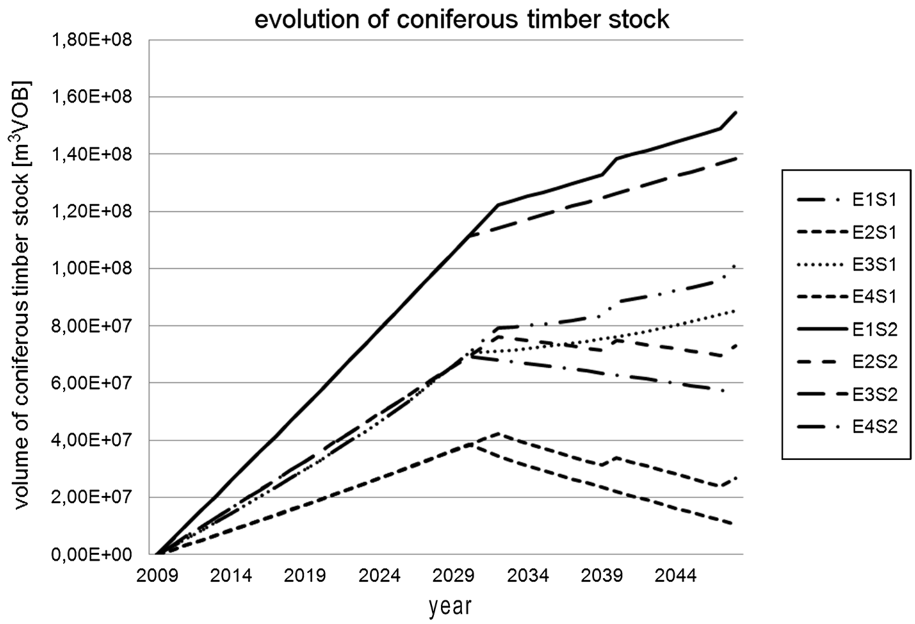

Fig. 4 Coniferous timber stock evolution in each experiment

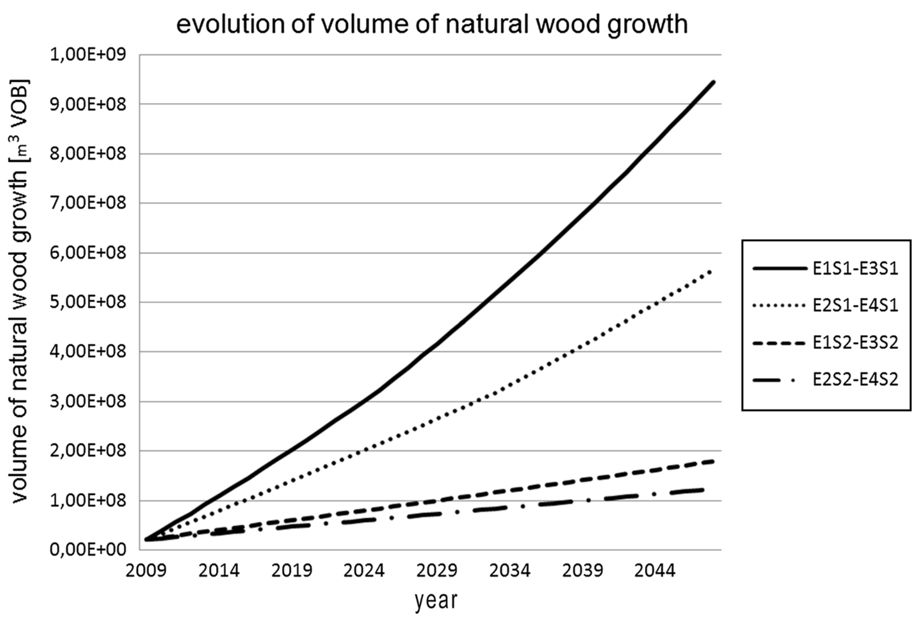

Fig. 5 Volume of natural wood growth in each experiment

proportional impact on its growth. It is fixed at 10.38 % of natural production.

Results and discussion

It is important to note that the *pob* and *poba* variables were unchanged in all of the simulations, as in the generation of the scenarios no demographic modifications were forecasted. They correspond fully with the forecasts made by the INE for population growth. The results for the study's target variable, *mte*, are shown in Fig. 4.

In scenario 1 which is the most likely, an increase in felling of 70 % increases available timber by 52 %, while the volume of natural growth is just 19 % with strategy 1.

In scenario 2, strategy 1 is unsustainable, as it would require timber for use in construction to be stored for 40 years, which is completely out of the question for the periods studied. With half of the timber production seen in E1-S1, 60 % of natural growth in forests is achieved (Fig. 5).

With a greater level of felling, present in strategy 2, the model becomes sustainable, with a volume equivalent to 50 % of that in E1-S2. It is surprising that with a natural growth rate which is half that seen in that experiment, 124 million m^3 VOB of natural wood growth is achieved, 69 %

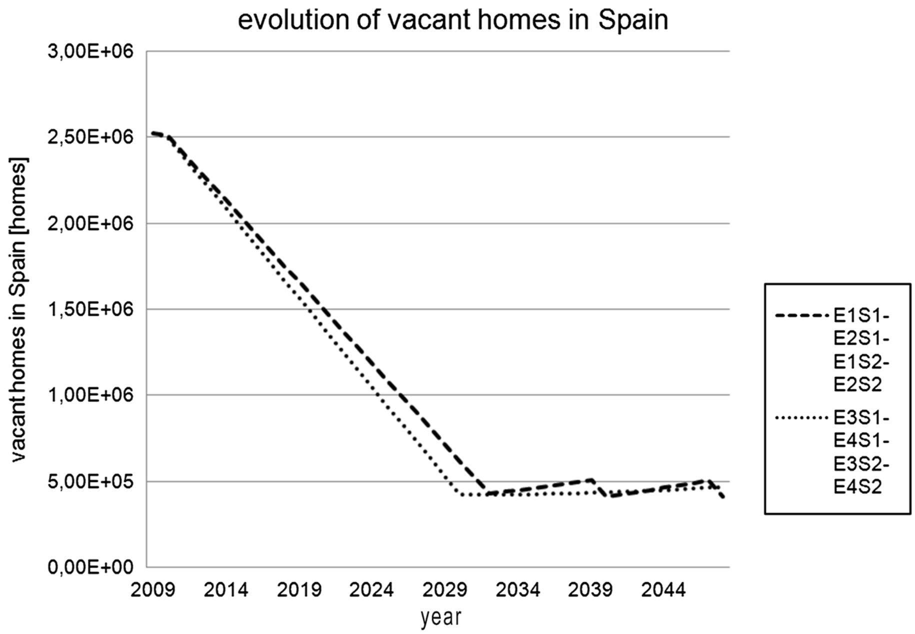

Fig. 6 Vacant homes in Spain in each experiment

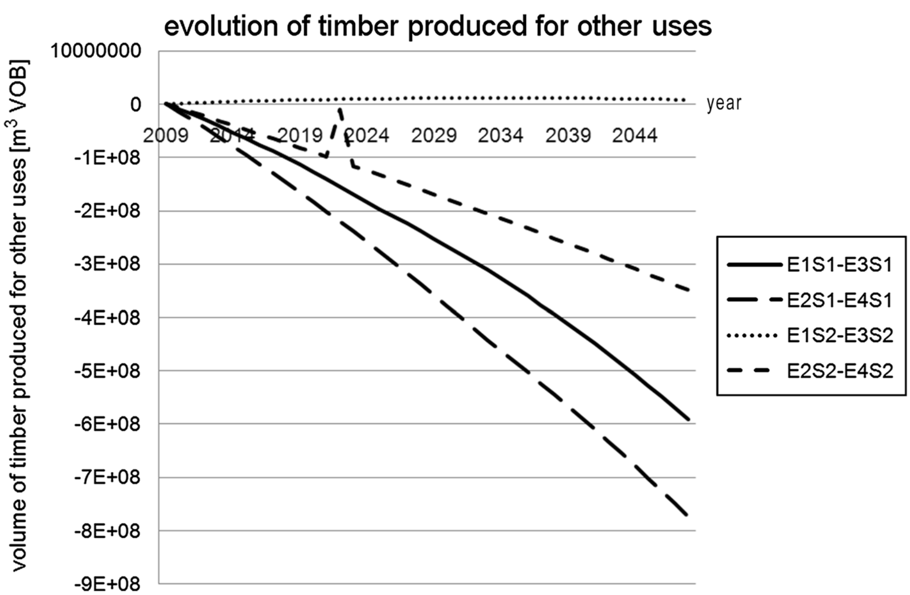

Fig. 7 Volume of timber produced for other uses in each experiment

of that seen in the other experiment. It is important to note that this model would require certain decisions to be made with regard to the storage of timber for several years due to the delay in the use of the timber for construction, caused by the asymmetric demand of the industry.

Scenarios 3 and 4 both posit a recovery period of the property sector lasting 24 years, until the maximum surplus stock of 500,000 homes is reached, due to the steep increase of 50 % in the demolition of homes, which impacts upon the automatic demand for homes (Fig. 6). In scenario 3, the effect of demand reduces the stock of timber for construction purposes by 18 and 11 % with strategies 1 and 2, respectively, which also see natural production of 945 million m^3 VOB and 179 million m^3 VOB, respectively,—a huge difference which is also seen between E1-S1 and E1-S2.

Scenario 4 is the most unfavourable for the objectives of the model to be achieved, as it combines a high rate of home demolition with a lower natural growth rate. Despite this, the use of strategy 2 leads to sustainability with regard to the timber production variable, obtaining the lowest value overall of 56.87 million m^3 VOB. As with experiment E2-S2, it would be necessary to take steps to store this timber, as after 2018, a new cycle begins, which may be essentially sustainable, but would be conditioned by the state of conservation of the previously felled timber.

The timber produced for the rest of the industry, m2, as observed in Fig. 7, would always have sustainable levels of production as long as natural growth falls within scenarios 1 and 3, and strategy 2 is followed, which involves an extraction rate of 70 %. Scenarios 2 and 4 would be unsustainable.

Conclusions

The coefficient of determination obtained validates the proposed model.

Most of the results displayed by the target variable in the experiments were positive. 75 % of the experiments are sustainable. This percentage generates enough timber for the entire construction industry (Fig. 4). Moreover, all the scenarios propose a sustainable exploitation of the Spanish forests, with a linear or exponential positive growth (Fig. 5). This demonstrates the feasibility of a situation which for most citizens has seemed unattainable, as it has previously been thought that the use of timber in construction would lead to deforestation and desertification.

This environmental sustainability also points to a pathway for wealth generation in the medium-to-long term, demonstrating that timber could represent an opportunity for desperately needed economic regeneration, while also providing us with grounds to claim that this study makes a useful contribution to knowledge (Anbumozhi et al. 2010).

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