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Life Cycle Analysis and Optimization of a Timber Building

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Abstract

The present study propose a thorough approach to the optimization of the whole-life cost of a timber building focusing mostly on its mechanical, structural and energy subsystems for a life cycle of 20 years. Another parameter that is examined, is the effect of the fuzziness of the design temperature inside a building on its life cycle cost. The objective function of the energy performance optimization problem of the study is a cost function. The components of the timber frame are optimized according to Eurocode 5. Two scenarios for the management of the timber frame components at the end of the building's life cycle are examined.

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Keywords: whole-life cost and structural optimization of timber building, cost functions

1. Introduction

The total life cycle cost of a specific system is dependent on the system's most critical components. These components can be identified through the examination of the system's life cycle stages, which -in the case of construction projects- are mainly the raw material acquisition stage and construction stage (initial cost), the operation/maintenance stage and the waste management stage that also co-estimates the remaining costs at the end of the system's expected life cycle. [1]. In the same manner that the environmental impact of the life cycle can be quantified and measured, the economic cost of the same system can also be estimated on a similar basis. In the latter case, the aim of the analysis is the calculation of the cost associated with the life cycle of the examined system or life cycle cost [2].

. The formula below is a generalized approach for a system's total life cycle cost:

$$LCC = C + PV_{RECURRING} - PV_{RESIDUAL\text{-}VALUE} \tag{1}$$

where

LCC is the total life cycle cost, C is the Year 0 initial cost, $PV_{RECURRING}$ is the present value of all recurring costs (utilities, maintenance costs, replacements, service costs etc.), $PV_{RESIDUAL\text{-}VALUE}$ is the present value of the residual value at the end of the examined life cycle period. The residual value is either considered to be equal to zero or it can be calculated through the following formula:

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$$PV_{RESIDUAL\text{-}VALUE} = \text{Subsystem's initial value* (Current year)/(Subsystem's total life cycle (in years))} \qquad (2)$$

In order for the life cycle cost of a specific building to be minimized, it is important to determine -during its design and construction stage- the subsystems that affect its life cycle cost with the view of taking optimal design decisions. In general, the following subsystems have a considerable impact on the life cycle cost of a building:

- Building Envelope (insulation profiles, shading systems, glazing, roofing etc.)
- Mechanical and Energy Systems (use of photovoltaic panels or alternative sources of energy, ventilation systems, water distribution systems etc.)
- Structural Systems (selection of appropriate frame materials, sizing of the frame components)
- Siting (landscaping and irrigation-related design decisions).
- Electrical Systems (lighting sources and control, distribution)

For typical cases of buildings in Greece, practical experience as well as data derived from statutory sources in building construction cost analysis studies, have shown that the most critical subsystems that affect its total whole life cost are those related to its massing, its structural and energy performance.

Apart from that, it is also necessary to consider the average life cycle of the above mentioned subsystems in order to predict any potential replacements that may occur during the examined life cycle period. These maintenance processes affect the life cycle of the examined system, both in environmental and in economic terms. Their estimated service life provides useful guidelines regarding their potential replacement or repair. According to various sources [3], [4], [5], the average life cycle of -frequently used- building materials and subsystems (that were considered in the present study either because they are invariably encountered in buildings or because of their popularity in the Greek market) is as follows:

- Building Exteriors, Doors, and Windows: 80 years (lifetime)
- Timber structural systems: 50 years (lifetime)
- Mineral wool insulation profiles: 50 years
- Photovoltaic panels: 25 years
- HVAC systems: 15-20 years
- Gypsum boards: 75 years

2. Methodology

The present study focused on optimizing a timber office building from a structural and an energy performance standpoint, after having conducted a life cycle analysis about its components. Noteworthily, it is one of the first published attempts to optimize the energy design of buildings according to KENAK [3], [4]; the recent Greek code for the energy design of buildings. There are also very few studies about the structural optimization of timber structural components according to Eurocode 5 [6].

2.1 Subsystems considered in the optimization problem and market research

At first, a market research took place in an attempt to discover average, real-life cost figures of the subsystems that would be used in the algorithm. Therefore the costs of the following subsystems were taken into consideration:

- Wall and roof inner & outer layers (gypsum boards and wood, respectively).
- Structural systems (selection of appropriate wooden frame materials, sizing of the frame components)
- Mineral wool insulation of various thicknesses.
- High energy class air-conditioning systems (A and A+++ energy class).
- Double and triple-glazed aluminum windows (with regular or low-e values).
- Photovoltaic system cost per kWp.
- Structural timber cost per m^3.

2.2 Initial considerations

It was assumed that the building will be used as an office building located on Athens, Greece and this influenced the considerations that were used in the optimization algorithm (thermal or cooling loads generated by the theoretical population of building users per sq.m., minimum required ventilation) that was created in Matlab. Since the algorithm was structured according to guidelines of KENAK [3], [4], it took into account the cost effect of the following parameters that affect the energy balance of the building: thermal conductivity of the envelope components, ventilation and solar gains [7]. The thermal bridges are also incorporated in the algorithm with the use of the approximate standardized values of the national standards [3], [4]. Furthermore, in order to save computational time and unify parameters that have an impact on each other and correlate energy performance parameters with the resultant cost, curve-fitting and multiple linear regression has been used. This resulted in the creation of cost functions for the windows and the thickness of the mineral wool insulation. The cost functions take advantage of the homogeneity of the above mentioned subsystems [7] and -some of the ones that were used in the algorithms- are demonstrated in order for the reader to be able to understand the logic behind that idea (see section 4, for explanation of the symbols):

$cost_{windowseast} = (218.376 - 38.931*U_{wineast} + 47.888*ggl)*A_{wineast}$ *(cost function correlating the energy parameters of a window with its cost)* (3)

$cost_{insulationwallwest} = (1.309* U_{wwest}^{-0.672})*A_{wwest}$ *(cost function correlating the u-value of the west wall with the mineral wool insulation thickness)* (4)

$costAC = -1000.434+172.14*POWERAC+179.306*SEER-2.05125*SCOP$ (*Air conditioning systems cost function describing A and A+++ energy class A/C systems*) (5)

The correlation results revealed (basing any judgment on the computed R-squared values of the cost functions that were produced through multiple linear regression), a very high degree of correlation implying a logical relationship between cost and critical energy performance parameters [7], [8].

2.3 Life cycle analysis

The life cycle analysis that took place was based on critical information about the rates, the service lives and the most expected decisions at the end of the building's life cycle. Such information can be found in the following software: ATHENA, BEES, Boustead, GaBi, SimaPro. The purpose of this information is to reflect what would more likely happen in an average situation [9]. As there are various combinations of environmental friendliness and economic efficiency scores that affect the design decisions, the present study based its assumptions on a score of 50% environmental friendliness and 50% economic efficiency, for each examined building component.

The LCA evidently influenced the main considerations regarding the life cycle costs of the examined subsystems that were later on introduced in the optimization algorithms. The main assumptions are the following:

- The mineral wool wall insulation profile is expected to end up in a landfill despite the fact that most of it can be recycled at the end of its useful life [9].
- The PV array requires (usually twice a year) periodic removal of the dust -concentrated on the panels- that affects its performance [10], [11] but this cost is negligible. Another cost that needs to be taken into account is the replacement of the inverter (information about the useful life of the inverter is provided by the guarantee, however excepting that its replacement would take place every 5-10 years is a legitimate assumption).
- The timber building envelope walls require some degree of regular maintenance in order for water penetration to the shell to be prevented. It is possible to predetermine a periodic maintenance plan that has a standard cost that is merely influenced by the inflation rates and the number of years [9], however the present study considered that building envelope maintenance costs are equal to 4% of their initial value with a start point five years after the building's construction. Two scenarios (A & B) for the management of the structural elements at the end of the building's life cycle are examined: deconstruction and reuse (A) or recycling (B) of the frame components.
- The gypsum boards are assumed that will end up in a landfill, despite the fact that they could be recyclable to some extent at the end of their useful life. Some degree of protection and maintenance is required [9].

By following a deterministic approach regarding the management of the building components at the end of the building's life cycle, the residual values of the subsystems as described in equation (2), that will not be reused or recycled, are ignored as they have no practical importance.

3. Setting up scenarios 1, 2, 3 that relate to the design temperature inside the building

The design temperature inside the building is a parameter dependent on the level of the thermal comfort of the users and is examined in this paper, as a fuzzy variable. In accordance with data from various sources [3], [4], a general comfort rule is to design an office building -in terms of its energy performance-, for an inside temperature of 22 ± 1^{o}C, during the winter period (15 October to 15 May) and 24.5 ± 1^{o}C, during the summer period (15 May to 15 October).

In the present study, it was decided to examine the impact of this temperature fluctuation on the optimal life cycle cost of a timber office building, for a period of 20 years. The resultant heating and cooling degree days [10] for any building located on Athens, Greece, are as follows:

HDD: *1730 (21 ^{o}C), 1930 (22 ^{o}C) 2135 (23 ^{o}C) &* ***CDD:*** *794 (23.5 ^{o}C), 679 (24.5 ^{o}C), 573.5 (25.5 ^{o}C).*

The optimization calculations took into consideration the following combinations of heating and cooling degree days (HDD resp. CDD):

- Scenario 1: HDD: 1730 (21 ^{o}C), CDD: 573.5 (25.5 ^{o}C) (Examined period: 20 years).
- Scenario 2: HDD: 1930 (22 ^{o}C), CDD: 679 (24.5 ^{o}C) (Examined period: 20 years).
- Scenario 3: HDD: 2135 (23 ^{o}C), CDD: 794 (23.5 ^{o}C) (Examined period: 20 years).

4. Optimization Variables

The following variables were taken into consideration in the optimization algorithm:

- U-value of floor (it is assumed that the building floor has a reinforced concrete slab, of 20 cm thickness, and below that a u-value results from the optimization procedure).
- U-values of walls (each orientation was examined separately; it is assumed that the outer layer of the walls consists of wooden panel with an R value equal to 0.12 and its thickness is equal to 5 cm, whereas the inner layer of the walls consists of a gypsum board panel and its thickness is also equal to 5 cm).
- U-value of roof (the roof has similar components with the walls).
- Area of windows (all elevations; each orientation was examined separately).
- ggl value (window solar gain coefficient multiplied by 0.75).
- Power of heating system.
- Power of cooling system.
- SCOP (Seasonal coefficient of performance of the heating system).
- SEER (Seasonal coefficient of performance of the cooling system).
- Heating energy needs (in kWh) during the day of winter that exhibits the lowest levels of solar irradiation that can be covered by a photovoltaic panel array, in a way that a 4-day autonomy is also ensured. The monthly expected levels of solar irradiation are taken from standardized tables and the PV panels considered to have an optimal inclination equal to 31^o that is optimal for Athens, Greece [3], [4], [11].
- Smaller and larger dimension (b and h, respectively) of each timber element of the timber frame.

5. Constraints for the energy performance optimization subproblem

The algorithm that was developed took into account the following constraints:

- The power of the heating system should be greater than the result of following formula that is used for the sizing of heating systems by the Greek specifications.

$$P\ thermal\ system > 1.8xU_m * A * \Delta T \tag{6}$$

Where: U_m is the average u-value of the exposed (to the atmospheric air) building envelope, A is the total area of the exposed building envelope, ΔT is a temperature difference used for the sizing of the thermal system and is increased through the multiplication by a coefficient that co-estimates losses etc [3], [4].

- The same should apply for the air conditioning system, whose power (in kilowatts) must be sufficient for the most adverse day of the summer (21st of July) [12].
- All the components of the building envelope should have acceptable lower and upper limits of u values. Therefore:
  1. U-values of walls: 0.20 < Uwalls < 0.50
  2. U-value of the floor: 0.20 < Ufloor < 0.90
  3. U-value of the roof: 0.20 < Uroof < 0.45
- The overall average u value of the building should be lower than what is required by the relevant specification (KENAK) [3], [4].
- The window u-values should be realistic and therefore they should not be lower than what can be encountered in the market [7].
- The seasonal coefficients SCOP for the heating system and SEER for the air-conditioning system should represent the upper and lower limits that are encountered in the Greek market [7].
- The total area of the building windows should ensure sufficient natural illumination and ventilation. According to the Greek building codes, this area should represent at least 10% of the total area of the building [7].
- The ggl values (hence, g values multiplied by 0.75; therefore reduced due to the contribution of the window frame that was considered to approximately occupy 25% of their total area) of windows should have a value between 0.29 and 0.55.
- For the purpose of sizing the photovoltaic array in an optimal way the variable in the optimization algorithm is the required energy in kWh (intending to cover merely the heating and cooling energy needs), for the most adverse day of the winter in way that a 4-day energy autonomy is ensured even for that day. Losses due to aging (expressed through a yearly performance reduction that can alternatively be estimated though an equivalent reduction coefficient equal to 0.90) [13], losses due to dust and snow (expressed through a reduction coefficient equal to 0.90) [13], inverter losses (expressed through a reduction coefficient equal to 0.875) [13], monthly temperature losses (expressed with a coefficient that estimates the influence of the outdoor temperature on the absorbed energy of the system by using average outdoor temperatures at a monthly step) [13], cable losses (expressed through a reduction coefficient equal to 0.98) are taken into account [11]. After the determination of the required energy in kWh, for the most adverse of the winter, it is possible for the peak power (kWp) of the photovoltaic system to be evaluated [11], [13]. After the evaluation of the peak power of the system it is possible to evaluate the area of the required area of the panels (through a coefficient translating kW into total panel area), the resultant cost of the PV system and the total energy that can be produced during the winter and the summer period. It is meaningful to note that the final panel area is rounded up to the next integer number of panels, in a way that therefore is ensured that the final area of panels is

always bigger than the required area that derives from the calculations. The present study, has used for its calculations merely one type of photovoltaic panels; panels with a known cost, area per kWp, efficiency and power parameters (245 Wp , nstc = 14.9%). This variable that was analyzed above can take a value between 0 and 10 kWh.

6. Model

The building that was used in the simulation is a single-storey timber building located on Athens, Greece. A plan view of the building as well as its left (and right) and front (and back) elevations -which has a 10x15 m rectangular shape- is shown in Fig.1. The examined life cycle period is 20 years and the building height is 3 m.

Apart from that, the following data were used for the optimization of the energy design of the building:

- The solar gains during the winter period (15 October to 15 May) are subtracted from the total thermal load; however, since they are not fully utilized they are reduced through a seasonal utilization factor. During the summer period (15 May to 15 October) the solar gains are added to the total cooling load and are again reduced by a seasonal utilization factor. The solar gains were calculated with the use of the approximate standardized values of the national standards for the specific geographic location [3], [4], [14]. It assumed that both the wall of the building envelope and the windows are shaded to a known extent, therefore a reduction factor of 50% applies. The color of the walls is assumed to be a nuance of grey.

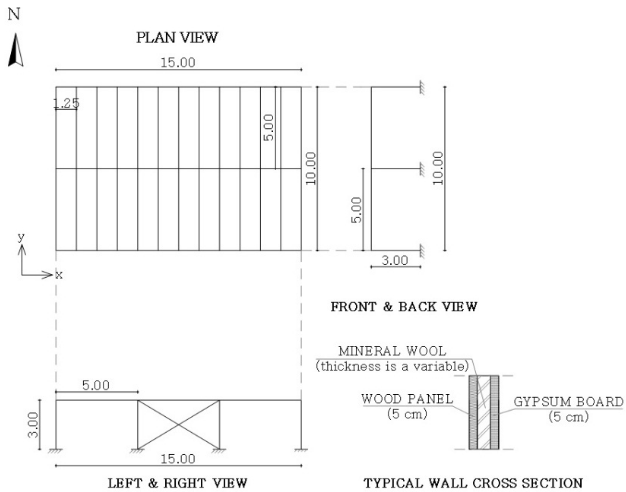

Figure 1: The analyzed timber building

- Coefficient accounting for the electricity cost in Euros/kWh = 0.07.
- Cost of the wall & roof profiles (inner and outer layers, excluding the mineral wool insulation): 25 € per m^2.
- Cost of the floor slab: 101 € per m^3.
- Photovoltaic system cost (€ per kWp): 2933.7.
- Cost of the timber structural elements: 350 € per m^3.

In accordance with the relevant specifications, it was also taken into account that the office building has an intermittent type of heating, a 5day working week and a 4hr occupancy and these considerations result in the selection of an appropriate correction factor that affects the estimation of the total energy consumption. [3], [4], [10], [14]. The maintenance rates for the building are considered to be equal to 1% of its initial value (therefore, unaffected by inflation rates) per year, with a start point five years after its construction. As regards the HVAC systems, the maintenance rate is considered to be equal to 2% of their initial value (unaffected by inflation rates) per year [15]. As regards the heating and cooling costs, it is also possible to use the predicted UPV values of the electricity costs 20 years after the construction of the building, however only predicted values from countries such as the USA, can be found.

6.1 Objective function for the energy performance optimization subproblem

The objective function describing the total life cycle cost is the sum of the costs of the following subsystems [7]:

*total cost = cost of insulation + Heating cost*Number of years + Cooling cost*Number of years + cost of A/C system + cost of windows + cost of roof + cost of walls + HVAC maintenance + general building maintenance + cost of the floor* *slab + cost of photovoltaic array + PV array maintenance costs + timber frame components costs +* $\sum_{i=1}^{i} p_i$ (7)

Each of terms p_i represents a particular constraint incorporated in the objective function. The value of the factors p_i is conditional; either equal to zero if a constraint is satisfied or equal to very high cost values exceeding the highest possible cost of the building if a constraint is not satisfied. Apart from that, the heating and cooling costs derive from the energy balance of the building (losses minus gains) and are multiplied by the previously mentioned coefficient that converts the energy needs (in kWh) into electricity costs.

7. Structural Optimization of the Timber Frame

The timber building's plan view as well as its elevations have been depicted in Fig.1. The loading that is applied on the side beams is equal to 5.39 kN/m and the loading of the intermediate beams is equal to 9.28 kN/m (for a loading combination 1.35G + 1.5Q, where G is the permanent load 5.78 kN/m, for the interior beams along the x-x axis, or 2.88 kN/m, for the side beams along the x-x axis, and Q is the moving load equal to: 1 kN/m). Apart from that, the specific weight of the timber elements is considered to be equal to 460 kg/m^3 (the category of the timber strength was considered to be C30 and each timber element were considered to be made of natural pine wood).

The beams are checked according to Eurocode 5 [6] for bending, shear and deflection. Similarly, each column is checked for compression, buckling and combined compression and bending. As regards the bounds for the optimization of the beam elements, the lower limit for b and h is 100 mm and the upper limit is equal to 800 mm. As regards the bounds for the optimization of the column elements, the upper limit for b and h is equal to 800 mm, whereas the lower limit is for b is 100 mm and 225 mm for h.

The optimization aims to the minimization of the cost of each timber structural element and takes place through the use of genetic algorithms and simulated annealing. In the same way with the methodology followed in the energy performance optimization, the constraints have been enforced by adding (to the computed cost of a particular beam or column element) conditional penalty functions that lead to very high cost values if a particular check is not satisfied. Another necessary condition that is ensured through a penalty function is related with the cross-section of the members, namely that h > b. More details about the optimization procedure are shown in the appendix.

8. Structural Optimization Results

A finite element analysis was conducted in SAP2000 under the assumptions that the structure behaves as 3D frame and that the beam-column connections are fixed [6]. After that, the maximum values of the axial and shear forces and bending moments that were observed in all the characteristic elements that constitute the structure were incorporated in the optimization program (Matlab). The optimization procedure requires -at least- ten runs for each element. After that the combination of dimensions resulting in the lowest cost are selected and rounded up to the closest multiple of 5 mm. The results are as follows:

- Side beams along y-y axis: b = 100 mm, h = 235 mm (Vsd = 15.71 kN, Msd = 14 kNm).
- Interior beams along y-y axis: b = 100 mm, h = 275 mm (Vsd = 29.43 kN, Msd = 22.76 kNm).
- Side beams along x-x axis: b = 100 mm, h = 360 mm (Vsd = 38.95 kN, Msd = 40.98 kNm).
- Interior beam along x-x axis: b = 220 mm, h = 400 mm (Vsd = 104.27 kN, Msd = 106.55 kNm).
- Interior columns: b = 140 mm, h = 225 mm (Nsd = 245.66 kN, Msd = 1.61 kNm).
- Side middle columns along x-x axis: b = 120 mm, h = 235 mm (Nsd = 84.05 kN, Msd = 12.04 kNm).
- Side middle columns along y-y axis: b = 110 mm, h = 230 mm (Nsd = 95.25 kN, Msd = 6.1 kNm).
- Corner columns: b = 100 mm, h = 225 mm (Nsd = 37.58 kN, Msd = 7.31 kNm).

The diagonal beams were sized with the following dimensions: b = 100 mm, h = 100 mm. The total cost of the timber frame is therefore equal to: 2436.28 € and its total weight is equal to 3201.97 kg.

9. Energy Performance Optimization Results

The optimization problem is possible to be solved with the use of simulated annealing and genetic algorithms (through the optimization toolbox of Matlab) and the first method seems to constantly produce better results. The energy performance optimization results that were produced by running several scenarios are shown in the Appendixes A and B providing also more details about the optimization procedure. An interpretation of the results regarding the three aforementioned scenarios can lead to the following conclusions:

- It seems to be a cost-effective decision to use window panels with very low g values. For all scenarios, the south elevation is the one that necessitates the lower u-values. Moreover, it seems that in no scenario opting for triple glazed windows in any elevation is a cost-effective decision. It is meaningful to note that the thermal bridges are incorporated into the window cost function and that all the examined window profiles were considered to have thermal breaks. The area occupied by the windows is every time dependent on the optimization calculations.

- In no optimization scenario the decision to cover part of the electricity needs for heating and cooling through a PV system of any size was a cost-effective decision.
- For all the aforementioned scenarios, the optimization program naturally places the largest window areas on the north elevation (hence, the elevation with the least amount of solar gains).
- The heating and cooling requirements of the office building can be covered with a 9000 Btu, A/C system of very high energy efficiency (falling into the energy class category A+++). It is meaningful to note that the simulation logic that was used in the algorithm considered that merely one A/C unit would be used. Evidently, in larger buildings there is potential for different simulation approaches and the number of the air conditioning system terminals could either be predefined or it could be a variable of the optimization problem.
- A change in the design internal building temperature of the building (within the acceptable limits), slightly affects the optimal solution, but not to a great extent. Nevertheless, in larger buildings, a greater degree of precision in the selection of the design temperature could lead to considerable cost savings.

10. Economic Implications of the Management of the Structural Elements at the End of the Building's Life Cycle

For the purpose of estimating in advance the optimal scenario -from a financial standpoint, namely the management of the structural members at end of the building’s life cycle, two scenarios (A & B) were examined.

Scenario A (deconstruction and reuse of the structural members that constitute the building’s frame) assumes that 80% of the structural elements of the building will be recovered and reused. The maintenance costs of the building’s frames per year are considered to be equal to 4% of the frames’ initial cost (unaffected by the inflation rates) and the inflation rates are considered to be equal to 3%. Scenario B (deconstruction and recycling of the structural members that constitute the building’s frame) assumes that 80% the timber material that constitutes the frames of the building can be recovered and that the earnings from the recycling process are equal to 0.90 € per kg of timber mass. The inflation rates are again considered to be equal to 3%. A table (Table 1) estimating the total life cycle cost of the building for both scenarios and all the examined heating and cooling degree days combinations is shown below:

MANAGEMENT SCENARIOS A & B	LCC + TIMBER FRAME MAINTENANCE	LCC COST MINUS REUSE PROFIT	LCC COST MINUS RECYCLING PROFIT
SCENARIO 1	31 697.35 €	30 618.23 €	30 305.37 €
SCENARIO 2	32 688.32 €	31 609.19 €	31 296.34 €
SCENARIO 3	34 369.42 €	33 290.30 €	32 977.44 €

Table 1: Total life cycle cost for scenarios A & B and all the examined heating and cooling degree days.

It can be observed that for the current rates the decision of recycling the timber frame components is more cost-effective than reusing them.

11. Fuzzy Analysis of the influence of the Heating & Cooling Degree Days on the Life Cycle Cost Function

The present study also seeks to propose a method to examine the effect of the fuzziness of the design temperature inside a building on its life cycle cost (LCC). Initially the total heating and cooling degree days (HDD and CDD respectively) that result from the fluctuation of the temperature inside the building are plotted in diagrams (Fig. 2) in a way that specific α-cuts denoting this fluctuation can be visualized [16]. The values for the rest of the building energy design variables were taken from the results of the optimization scenario 3. The response of the total life cycle cost function for all the aforementioned HDD & CDD α-cuts is calculated, and the calculations results are plotted with a similar philosophy [16]. It can be observed that the total life cycle cost function (Fig. 2) displays a high degree of linearity when it is correlated with the heating and cooling degree days.

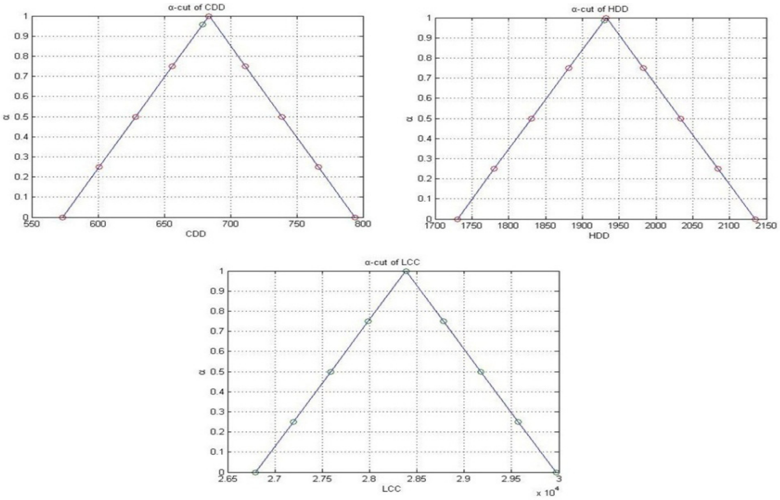

Fig 2: Results of the fuzzy analysis.

12. Conclusions

A life cycle analysis of a timber building has been carried out that takes into account energy considerations for construction and material costs, as well as energy consumption during usage of the structure. A structural analysis is conducted, followed by structural optimization of the timber components. Both LCA and structural optimization are solved together with the use of simulated annealing and genetic algorithms. By this way an optimal design of a timber building on the side of the energy consumption during its life cycle can be achieved. In addition the effect of the fuzziness of the design temperature inside a building on its life cycle cost has been considered by using fuzzy analysis tools. Further investigation will take into account additional factors that potentially influence the LCA and the structural optimization results, like the labour and plant costs.

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Appendix A. Results of the optimization calculations (energy, building envelope and mechanical subsystems)

SCENARIO 1	HDD: 1730, CDD: 573.5																			
	U_{floor}	SCOP	ggl	$A_{winsouth}$	$A_{winnorth}$	$A_{wineast}$	$A_{winwest}$	U_{roof}	$U_{wall\ south}$	$U_{wall\ north}$	$U_{wall\ east}$	$U_{wall\ west}$	$U_{win\ south}$	$U_{win\ north}$	$U_{win\ east}$	$U_{winwest}$	Power of HVAC system	SEER	Peak energy needs covered by PV array (kWh)	LCC EXCLUDING FRAME MAINTENANCE
	0.899	8.000	0.292	0.511	8.800	0.506	5.186	0.450	0.393	0.459	0.477	0.490	3.206	3.384	3.061	3.398	2.501	5.600	0.000	27312.050
SCENARIO 2	HDD: 1930, CDD: 679																			
	U_{floor}	SCOP	ggl	$A_{winsouth}$	$A_{winnorth}$	$A_{wineast}$	$A_{winwest}$	U_{roof}	$U_{wall\ south}$	$U_{wall\ north}$	$U_{wall\ east}$	$U_{wall\ west}$	$U_{win\ south}$	$U_{win\ north}$	$U_{win\ east}$	$U_{winwest}$	Power of HVAC system	SEER	Peak energy needs covered by PV array (kWh)	LCC EXCLUDING FRAME MAINTENANCE
	0.900	8.000	0.291	0.500	13.571	0.500	0.501	0.450	0.499	0.492	0.465	0.499	3.236	3.175	3.396	3.258	2.500	5.600	0.000	28303.018
SCENARIO 3	HDD: 2135, CDD: 794																			
	U_{floor}	SCOP	ggl	$A_{winsouth}$	$A_{winnorth}$	$A_{wineast}$	$A_{winwest}$	U_{roof}	$U_{wall\ south}$	$U_{wall\ north}$	$U_{wall\ east}$	$U_{wall\ west}$	$U_{win\ south}$	$U_{win\ north}$	$U_{win\ east}$	$U_{winwest}$	Power of HVAC system	SEER	Peak energy needs covered by PV array (kWh)	LCC EXCLUDING FRAME MAINTENANCE
	0.899	8.000	0.291	0.500	14.724	0.501	0.513	0.450	0.340	0.288	0.493	0.456	2.869	3.201	3.070	3.109	2.500	5.600	0.000	29984.120

Appendix B. The authors have generally made use of the preset options of Matlab's optimization toolbox making only very few adjustments. Critical information about the options used both for the energy performance subproblem and for the structural optimization subproblem are as follows: GENETIC ALGORITHMS: Fitness scaling is based on rank, the initial population can have iteratively any size from 100 to 1000, the function selection is stochastic and uniform, a scattered crossover function is used, the mutation function is constraint dependent. SIMULATED ANNEALING: Exponential function update, the maximum number of function evaluations is equal to 3000*Number of variables, a fast annealing function is used. Both simulated annealing and genetic algorithms are effective as optimization methods for the structural and the energy performance subproblem. GA is more effective for the structural optimization subproblem, while SA is more effective for the energy performance subproblem. At least ten runs (per optimization method) are required to ensure that the local minimum found at the end of each optimization trial, constitutes a good global optimal solution.

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