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Analysis of the environmental, economic, thermal and energy performances of green building technologies

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Abstract. Nowadays, the construction sector must comply with increasingly high-performances and sustainability instances. To meet multiple requirements, it is important to apply a multi-criteria design approach, which allows the designer to analyze, evaluate, choose, and summarize the parameters to pay attention to in pursuit of building quality. A conscious use of green materials and technologies avoid the risk of greenwashing, which is common both in production and construction.
This contribution investigates the performances of different green building construction solutions. Moreover, it compares them with the performances of commonly adopted technological solutions in contemporary construction.
The methodology adopted in the investigation provides for the realization of a multi-criteria analysis in which thermal, energy performances, environmental and economic costs associated with these technologies are assessed. These considerations are contextualized in the case of new construction in a Mediterranean climate.
The conclusions highlight how complex it is to identify a single building technology that optimizes all the performance criteria chosen. Proper design must consider several factors such as local climate, environmental context, and planovolumetric design to maximize the performance of the selected criterion.

Key words. green buildings, sustainable design, thermal and energy performance, embodied carbon, costs.

1. Introduction

Architecture, engineering and construction sector is responsible for nearly 40% of total CO_2 emissions, more than a third of global energy consumption (36%) [1] and 33% of annual waste generation in Europe [2]. The built environment has a strong impact on the natural environment and quality of life; although these have always been a constant in human history, the impacts of the sector have significantly increased [3] and seem set to grow further. Current scenarios and future forecasts indicate that a revolution in the construction sector is needed [4]. In this sense, sustainable design approaches have taken on global importance as basic parameters for the management of buildings during the coming years. In response to the energy crisis and the worsening of environmental conditions, green buildings have emerged, resulting in the introduction of innovative building technologies and the rediscovery of ancient techniques based on the use of natural materials. There is a need to consider the use of natural materials in the context of civil construction; this would allow architecture a more sustainable future, due to their low environmental impact, high recyclability, low consumption of non-renewable resources [5]. At the same time, the construction sector, and in particular public procurements, today require performance-based design with quantitative guarantees of expected results. To respond to the sustainability challenge, the construction market must propose economic and sustainable products that are certifiable

because of a controlled and standardized production process so as not to run into greenwashing risks [6].
In the following, a study is proposed to verify and compare the performance of building technologies based on the use of natural materials. We analyzed and compared the performances, in terms of incorporated carbon, internal comfort, energy requirement, costs, building envelope performance and internal air temperature, of nine different construction solutions (eight green building technologies and one commonly adopted solution in the construction market). A dynamic multi-criteria energy analysis was conducted on a case study model in a mild temperate climate area (Csa - Koppen classification) with the use of the Energy Plus calculation code and Design Builder 6.0 graphical interface.

2. The investigated technologies

Nine different building technologies were considered in this analysis. The taxonomy considered technologies which are widely used in the green building market (CLT, Platform frame -PF-, Straw Bale -SB- and Wood cement formwork -WCF- blocks), recently introduced technologies (CobBauge, Sirewall, Sistema mixto -SM-, Mod_RE), and a conventional technology in the construction industry (Porotherm technology). The basic horizontal closure was assumed to be the same for all building technologies (table I), while the vertical closure (table II) and the horizontal roof closure (table III) were designed differently for each one. The basic constructions used for the building components of each investigated technology are shown in the tables I-III. Reported data are taken from the literature and regard thermal properties, costs and embodied carbon of the materials used.
While cross laminated timber and platform frame are well-known and diffused timber-based technologies, straw bale construction is nowadays experiencing a wide diffusion [7] thanks to the good thermal insulating properties of straw bales [8]. Wood-cement formwork blocks have a good diffusion because they allow a quick construction process of composite walls. Raw earth-based construction is at the center of innovation in green buildings, as suggested by the development of several constructive technologies in recent years: CobBauge (which uses a composite wall comprising a loadbearing cob wall and an insulating lightweight earth layer [9]), Sirewall (a cavity wall with two layers of cement-stabilized rammed earth reinforced with steel rods, with a synthetic board insulation interposed [10]), Sistema mixto (a coupled timber framed structure to which prefabricated lightened earth panels and timber bracings are fixed both on the internal and external side [11]) and Mod_Re (a load-bearing rammed earth wall designed to withstand earthquakes thanks to the reinforcement system composed of vertical and horizontal elements in timber and nylon/polyester ropes [12]). Finally, the Porotherm block technology, which is the most used in Italian building stock, has been used as benchmark.

Table I. – Construction of solid ground floor for all the investigated technologies

Materials	s [m]	ρ [kg/m³]	c [J/kg K]	λ [W/m K]	Emb. Carbon [$kgCO_2$/kg]	Costs [GBP]
Timber Flooring	0.01	650	1200	0.14	0.46	50.00
Polyethylene sheet	0.003	980	1800	0.5	1.94	4.00
Cork Board	0.05	160	1890	0.04	0.19	35.00
Fibreboard	0.015	300	1000	0.06	0.51	10.00
Dry Sand	0.08	1700	1000	0.6	0.02	1.00 [kg]
Fibreboard	0.02	300	1000	0.06	0.51	10.00
Air Layer Un. Floor	0.15	-	-	-	-	-
Reinf. Concrete	0.6	2300	1000	2.3	0.26	1.00 [kg]
Cast Concrete	0.1	2000	1000	1.13	0.08	1.00 [kg]

Table II. – Constructions of vertical closures

Materials	s [m]	ρ [kg/m³]	c [J/kg K]	λ [W/m K]	Emb. Carbon [$kgCO_2$/kg]	Costs [GBP]
CLT						
Plasterboard panel	0.015	95	840	0.16	0.51	30.00
Hemp mat	0.03	55	1700	0.034	0.079	15.30
5-layer CLT panel	0.10	500	1600	0.13	0.44	60.00
Hemp mat	0.05	55	1700	0.034	0.079	15.30
Fiber cement panel	0.02	350	1890	0.08	0.6	25.00
Lime plaster	0.03	1600	1000	0.8	0.01	20.00
PF						
Plasterboard panel	0.015	95	840	0.16	0.51	30.00
Hemp mat	0.03	55	1700	0.034	0.079	15.30
OSB Structural Panel	0.02	650	1700	0.13	0.43	10.00
Hemp mat	0.05	55	1700	0.034	0.079	15.30
OSB Structural Panel	0.02	650	1700	0.13	0.43	10.00
Air gap	0.03	-	-	-	-	-
Fiber cement panel	0.02	350	1890	0.08	0.6	25.00
Lime plaster	0.03	1600	1000	0.8	0.01	20.00
SB						
Earth render	0.025	2000	1000	1.1	0.02	30.00
Wooden planking	0.02	900	2000	0.13	0.86	20.00
Straw bales	0.45	100	600	0.069	0.01	20.41 [m³]
Wooden planking	0.02	900	2000	0.13	0.86	20.00
Lime plaster	0.025	1600	1000	0.8	0.01	20.00
CobBauge						
Earth render	0.03	2000	1000	1.1	0.02	30.00

Cob with 5% straw	0.25	1423	900	0.44	0.08	3.50
Lightweight earth with 50% hemp	0.30	340	900	0.11	0.077	20.00
Lime plaster	0.03	1600	1000	0.8	0.01	20.00
SIREWALL						
Cement stabilized RE	0.30	1900	868	0.643	0.21	0.30 [kg]
EPS	0.10	15	1400	0.04	2.5	7.00
Cement stabilized RE	0.20	1900	868	0.643	0.21	0.30 [kg]
SM						
Earthen plaster	0.025	2000	1000	1.1	0.02	30.00
Lightweight Earth panel with straw	0.07	721	900	0.122	0.077	1.20
Air gap	0.03	-	-	-	-	-
Lightweight Earth panel with straw	0.07	721	900	0.122	0.077	1.20
Cork panel	0.06	160	1890	0.04	0.19	35.00
Lime plaster	0.025	1600	1000	0.8	0.01	20.00
Mod_RE						
Earth render	0.025	2000	1000	1.1	0.02	30.00
Rammed earth	0.40	1950	1000	0.508	0.08	0.36 [kg]
Thermal plaster	0.15	400	1500	0.085	0.2	20.00
WCF blocks						
Plaster	0.025	1800	900	1.00	0.01	7.00
WCF blocks	0.38	510	1500	0.094	0.95	55.00
Plaster	0.025	1800	900	1.00	0.01	7.00
Porotherm						
Plaster	0.025	1800	900	1.00	0.01	7.00
Porotherm	0.36	640	1000	0.089	0.28	-
Plaster	0.025	1800	900	1.00	0.01	7.00

Table III. – Constructions of roof closures

Materials	s [m]	ρ [kg/m^3]	c [J/kg K]	λ [W/m K]	Emb. Carbon [kgCO$_2$/kg]	Costs [GBP]
Type A (CLT)						
Gravel	0.03	1840	840	0.36	0.02	20.00
Waterpr. Membrane	0.004	960	837	0.16	-	15.00
OSB Str. Panel	0.02	650	1700	0.13	0.43	10.00
Expanded clay	0.05	400	1000	0.09	0.39	77.00 [m^3]
OSB Str. Panel	0.02	650	1700	0.13	0.43	10.00
Vapor Barrier	0.001	625	1000	0.22	-	3.40
5-layer CLT panel	0.10	500	1600	0.13	0.44	60.00
Vapor Barrier	0.001	625	1000	0.22	-	3.40
Hemp mat	0.03	55	1700	0.034	0.079	15.30
Vapor Barrier	0.001	625	1000	0.22	-	3.40
Wooden Board	0.02	900	2000	0.13	0.86	20.00
Type B (PF, SB, CobBauge, SIREWALL, SM, Mod_RE)						
Gravel	0.03	1840	840	0.36	0.02	20.00
Waterpr. Membrane	0.004	960	837	0.16	-	15.00
OSB Str. Panel	0.02	650	1700	0.13	0.43	10.00
Expanded clay	0.05	400	1000	0.09	0.39	77.00 [m^3]
OSB Str. Panel	0.02	650	1700	0.13	0.43	10.00
Hemp mat	0.06	55	1700	0.034	0.079	15.30
Vapor Barrier	0.001	625	1000	0.22	-	3.40
OSB Str Panel	0.02	650	1700	0.13	0.43	10.00
Fir matchboarding	0.02	400	2100	0.11	0.90	16.39 [m^3]
Type C (WCF blocks)						
Gravel	0.03	1840	840	0.36	0.02	20.00
Waterpr. Membrane	0.004	960	837	0.16	-	15.00
Lightweight concrete	0.05	1400	840	0.6	0.13	20.00
Vapor Barrier	0.001	625	1000	0.22	-	3.40
Cork ins. panel	0.09	160	1890	0.04	0.19	35.00
Vapor Barrier	0.001	625	1000	0.22	-	3.40
Concrete slab	0.04	2000	1000	1.13	0.08	1.00 [kg]
WCF blocks & conc. joist	0.25	510	1500	0.22	0.94	100.00
Plaster	0.025	1800	900	1.00	0.01	7.00
Type D (Porotherm)						
Gravel	0.03	1840	840	0.36	0.02	20.00
Waterpr. Membrane	0.004	960	837	0.16	-	15.00
Lightweight concrete	0.05	1400	840	0.6	0.13	20.00
Vapor Barrier	0.001	625	1000	0.22	-	3.40
Cork ins. panel	0.09	160	1890	0.04	0.19	35.00
Vapor Barrier	0.001	625	1000	0.22	-	3.40
Hollow clay blocks & conc. slab	0.29	1400	1000	0.8	0.22	100.00
Plaster	0.025	1800	900	1.00	0.01	7.00
Gravel	0.03	1840	840	0.36	0.02	20.00

3. Methods

A. Building simulation modelling

The multicriteria investigation has been performed with the energy dynamic building tool Design Builder. Dynamic numerical simulations were performed on a yearly basis through the software Design Builder, both in free-running conditions (for analysis concerninng the building envelope's performances) and with an air-conditioning (AC) system (for analysis referred to annual energy needs).

The case study is a rectangular residential building, with three rooms on the south exposition and two rooms on the sides. The main geometric features of the building are shown in table IV:

Table IV. - Geometrical features of the building model

Heated gross volume	V	261.4	m^3
Total opaque surface	S_o	825.9	m^2
Total transparent surface	S_t	4.9	m^2
Total external surface	S	830.8	m^2
Shape factor	S/V	3.17	m^{-1}
Transparent/total rate	S_o/S_t	0.0059	-
Net floor area	S_u	58.92	m^2

As abovementioned, the basic constructions used for the building components of each investigated technology, shown in tables I-III, have been implemented on Design Builder software.

Windows are realised with a 5-cm oak wood frame and a double 6-mm glazing and 13-mm air gap. The overall thermal transmittance value of the windows is 3.00 W/m^2 K, and the solar heat gain coefficient (glass g-value) is 0.75.

In Design Builder model, all rooms of the reference residential building were considered as occupied zones. Internal loads of 16 W/m^2 were considered to describe the presence of occupants, electrical devices, cooking and lighting systems. The same internal heat loads are fixed for all the proposed configurations of simulations. For infiltration of outdoor air, a constant air change rate of 0.5 vol/h was set up.

Under the AC system scenario, the building is equipped with a heat pump (HP) system that supplies both heating and cooling. A HP system with a coefficient of performance (SCOP = 3.50) and energy efficiency ratio (EER = 2.50) when it operates as chiller was used. The calculation of the overall thermal energy needs of the building was carried out considering two operation programs as established by Italian laws [14] for heating and cooling season, respectively. The conditioning system operates with a set-point temperature of 20 °C during heating season, 26 °C in cooling season and with a relative humidity of 50%.

The meteorological data of the Energy Plus Weather (EPW) file for the city of Catania updated to the year 2019 were used as weather input for dynamic thermal simulations.

B. Objectives of the analysis

The comparison between the various technological solutions was carried out following a multicriteria approach, evaluating their performances regarding the following parameters:

- Embodied Carbon (annual);
- Indoor comfort (annual);
- Energy needs (annual);
- Economic Costs;
- Performance of the building envelope (during summer period);
- Indoor air temperature (maximum and minimum value in summer and winter period).

The analysis to assess embodied carbon, indoor comfort, energy requirements, and economic costs was performed using Design Builder's Optimization Tool, which allows comparison of several variables (in this case, the vertical and horizontal roof closures) with two main objectives (chosen among economic cost, comfort, environmental impact, etc.). Six analyses were then carried out where two objectives were compared at a time, keeping fixed the objective relating to the minimization of energy needs for heating and cooling.

Embodied carbon was evaluated using data related to each of the materials used; Design Builder offered an extensive database related to embodied carbon; values missing were derived from the ICE database. The parameter was analyzed to identify the building technology which can minimize GHG emissions.

Indoor discomfort hours were estimated according to [15], considering environmental and personal factors as indoor air temperature, average radiant temperature, relative air humidity, air velocity, metabolic rate, occupant clothing, that are critical to determining indoor comfort. Discomfort hours were calculated based on when the combination of humidity and operating temperature was outside the region considered acceptable by the standard.

The energy needs parameter is related to the energy performance and indicates the amount of energy required to meet the requirements related to a standard use of a building, annually, for heating, cooling, ventilation, production of domestic hot water [16]. It is directly related to indoor (comfort level of temperature, air quality and light) and outdoor climate conditions (temperature, solar radiation and wind) for working and living activities in buildings. As known, minimum energy performance requirements are set for insulation levels of walls, roof, floor and windows, etc. In this analysis, energy needs were deduced from the power supplied by the air conditioning system.

The cost analysis was carried out considering the costs of all materials used in each of the technologies and is quantified in GBP (pound sterling).

The performances of the building envelope were assessed in terms of decrement factor (the ratio between the amplitude of inner surface temperature fluctuation and that of outer surface temperature fluctuation) and time lag (time required for a temperature wave to be transferred from the outer surface of the wall to its inner surface). In this analysis endogenous loads and the heating and cooling systems were excluded because they tend to alter the behavior of the wall (free-running conditions) [17-19]. The indoor air temperature was evaluated considering the endogenous loads as these have a fundamental contribution on the temperature profiles of indoor air [13, 17].

4. Results and discussion

The results obtained from the evaluation of the embodied carbon showed that the Sistema mixto (59,461 kg), the platform frame (60,003 kg) and the straw bale technology (61,655 kg) are those which are able to minimize this parameter. On the other hand, Sirewall (79,269 kg), wood cement formwork blocks (85,801 kg) and Porotherm systems (70,517 kg) are the technologies with the highest embodied carbon values.

Straw bale (3,761 h), platform frame (3,770 h) and CLT (3,816 h) offer the lowest number of discomfort hours per year; even wood cement formwork blocks perform well in this regard (3,818 h), while other analyzed technologies show higher discomfort hours.

The evaluation of energy needs was carried out by considering the annual energy needs for heating and cooling. The minimization of the annual energy demand is achieved with the solution that uses straw bales (1133.3 kWh), then followed by the wood cement formwork blocks (1215.4 kWh) and the platform frame system (1244.3 kWh).

Economic cost minimization was found with the CobBauge earthen technology (234,244 GBP), being the low cost of the materials used a major factor in obtaining this result. Platform frame (242,756 GBP) and straw bale technology (237,350 GBP) also tend to minimize costs. As reported elsewhere, the cost of the Mod_RE technology could be halved if the soil present on site is used to build the walls [12].

As known, a non-air-conditioned building is strongly affected by the orientation of the sun and the thermal inertia of its building components; the analysis of building envelope performances showed that the Mod_RE technology has the lowest decrement factor (0.0073) and the highest time lag (15:12 h) among the investigated solutions. The CobBauge technology has the second-best performances (DF= 0.0090 and TL=14.36 h). These results emphasize the renown good performances of raw earth-based massive technologies in Mediterranean climate areas, during summer period. On the contrary, the results also highlight the worse performances of lightweight constructive systems in similar climatic conditions.

The indoor air temperature was evaluated both in a representative winter and summer period. Indeed, it is a parameter of fundamental importance for the evaluation of indoor thermal comfort. During the winter period, the analysis showed that the construction technology using straw bale has the best performance while lightweight timber-based systems, such as CLT, have the worst performances. During summer period, Mod_RE construction technology and wood-cement formwork blocks have the best performances.

To synthetize the whole analysis and easier its comprehension, results of each technology were normalized with respect to the best performance for each parameter and reported in a radar graph reported in fig. 1. The radar graph expresses all the parameters evaluated in the multicriteria analysis and the performance of each construction technology in relation to each of them. The center of the radar represents the worst performance, while its vertexes represent the best performances for each parameter.

5. Conclusions

This study focused on the analysis of various performances of green building technologies and compared them with a commonly adopted technology in the Italian building scene (Porotherm construction system). The analysis was conducted on a representative residential building ideally located in a Mediterranean climate. During the study, the behavior of nine different green building technologies was evaluated under various aspects, using Design Builder software and meteorological data collected for the city of Catania in 2019.

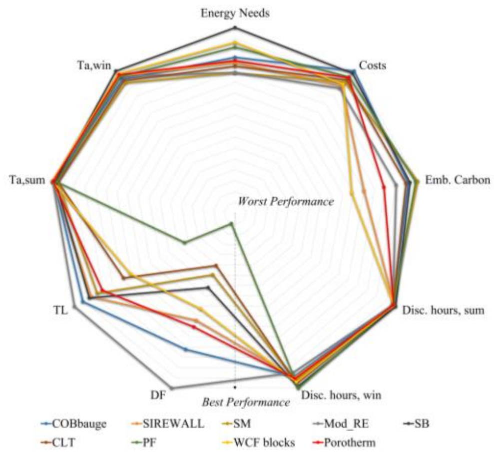

Fig. 1. Radar graph with multicriteria analysis results

Table V: Multicriteria analysis results for the investigated green building technologies

	CO_2 [kg]	Disc. Hours [h]	Energy Needs [kWh]	Costs [GBP]	DF [-]	TL [h]	$T_{a,sum}$ [°C]	$T_{a,win}$ [°C]
CLT	62,862	3,816	1377	247,431	0.018	11:40	28.9	17.2
PF	60,003	3,770	1244	242,756	0.037	7:17	28.7	17.7
SB	61,655	3,761	1133	237,350	0.014	14:08	28.5	18.3
Cob Bauge	62,193	3,880	1312	234,244	0.009	14:36	28.3	17.4
Sire wall	79,269	3,853	1349	256,877	0.011	14:00	28.3	17.7
SM	59,461	3,851	1429	250,544	0.016	13:34	28.8	17.0
Mod_RE	66,077	3,917	1425	260,942	0.007	15:12	28.1	17.7
WCF blocks	85,801	3,818	1215	254,201	0.012	14:45	28.1	18.0
Porotherm	70,517	3,852	1336	243,877	0.010	13:12	28.2	17.9

The obtained results lead us to state that:

- Technologies using natural materials have a lower environmental impact than both conventional and more industrialized materials; indeed, the Sistema mixto has the lowest embodied carbon value (59,461 kg);
- The minimization of discomfort hours, in both summer and winter conditions, was achieved with the platform frame and straw bale technologies (3,770 and 3,761 hours respectively);
- The lowest energy needs for space heating and cooling are found with the straw bale technology (1133.3 kWh);
- Sustainable building technologies can also be inexpensive; indeed, CobBauge technology is the one which minimizes material costs among all the investigated systems (234,244 GBP);
- The use of massive materials such as rammed earth and cob (Mod_RE and CobBauge systems) keeps interior surface temperature almost constant compared to the profile of exterior surface temperature; this results in low decrement factor and high time lag values (respectively 0.007 and 15:12 for Mod_RE, 0.009 and 14:36 for CobBauge). Regarding dynamic performances, lightweight constructive systems (like CLT, Platform frame and Sistema mixto) seem to be less suitable for Mediterranean climates;
- The mean indoor air temperature in winter conditions is nearer to the comfort one in the case of the straw bale construction technology (18.3 °C); in summer conditions, massive systems as Mod_RE and CobBauge maintain a better mean indoor air temperature compared to other examined technologies (both around 28.1 °C) without use of AC systems.

In conclusion, it can be stated that it is complex to identify a single construction system that optimizes all the considered parameters. It is appropriate, for a proper building and envelope design, to adopt a multi-criteria design approach which consider the criteria which want to be maximized, based on various factors that affect the design (local climate, building type, geometry, and orientation of the building, etc.).

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