Detail of Dominus Winery, California,
designed by Herzog & De Meuron with a dry construction system

Dominus Winery's detail, California (1997), designed by Herzog & De Meuron, with a "dry construction system"

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Evaluation of environmental sustainability threshold of "humid" and "dry" building systems, for reduction of embodied carbon (CO2)

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ABSTRACT

The New Italian Procurement Code (Legislative Decree No. 50/2016), in compliance with the EU direc-tives 26/02/2014, has introduced, among other things, the possibility of obtaining awards, during the awarding of the contract , in terms of reducing the estimated energy impact in the life cycle of the work. The objective of this study was to direct architectural design towards conscious choices that are compatible with environmental legislation. The study, therefore, aimed to analyze the characteristics of the most widespread (wet and dry) construction systems, in order to determine environmental sustainability thresholds referring to each of the four systems hypothesized for the development of the model.
The simulated cases for the definition of the model refer to the following construction systems: M1 (structural system in load-bearing masonry); M2 (constructive system with frame structure and traditional brick cladding); M3 (constructive system with metallic bearing structure and dry stratified shell); M4 (constructive system with wooden supporting structure and dry stratified shell).
The results indicated design scenarios aimed at using constructive systems that present advantages in terms of disassembly, recovery and reuse of the various components; in addition to the attitude of such systems, to be resilient, or to be able to be adapted and transformed during the life cycle of the building organism.

KEYWORDS
sustainable architecture design, eco-architecture, embodied energy, embodied carbon, life cycle assessment

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1. INTRODUCTION: CONSIDERATIONS ON THE BUILDING LIFE CYCLE

Sustainability, in architecture, means designing and constructing buildings to limit the impact on the environment, setting as requirements such as energy efficiency, improvement of health, comfort and quality of use of the inhabitants, etc.
The concept of sustainability, in addition to the management of all the anthropic activities that determine the exploitation of non-renewable re-sources, concerns, in a priority, the construction sector, one of the sectors most responsible for the consumption of soil, energy and resources with an incidence of about 30% compared to the total energy consumption, and 40% of the re-spective CO^2 emissions related to energy (source: http://www.rinnovabili.it/greenbuilding/consumption-building/).
The environmental impact is relevant not only during the construction and operation phase but also in the other phases of the building life cy-cle: extraction of the raw material, production, transport, demolition, disposal, according to a linear mechanism, from the cradle to the grave. The Life Cycle Assessment is a methodology that allows to formulate evaluations on a set of interactions between a product, a process or an activity and the ecosystem. Its main purpose is to evaluate the environmental impact of each of the phases of the entire life cycle, in order to be able to act strategically to limit the environmental impact, through the reduction of energy consumption and the consequent emissions of greenhouse gases in the atmosphere, according to the "cradle to cradle" concept developed by Braungart and McDonough (2002).
In recent years, the scientific debate focused on improving the performance efficiency of components and building subsystems, primarily the building envelope, requiring increasingly high performance of the technological components, to reduce consumption in the building operation phase . This strategy has, in fact, shifted energy consumption to other phases of the life cycle, such as the demolition and decommissioning of the building product.

1.1 THE NEW ITALIAN PROCUREMENT CODE (EUROPEAN DIRECTIVES EU, 26/02/2014)

The innovations introduced by the new Code of the Italian Procurement (Legislative Decree No. 50/2016 and subsequent corrective 56/2017), in compliance with the European directives EU 23-24-25 of 26/02/2014, make reference to the compulsory provisions of the Minimum Environmental Criteria, basic and rewarding, with reference to the economically most advantageous offer, according to the award criteria provided for by Article 95 of the Code, with regard to the qualitative aspects, environmental and social.
In particular, the most economically advantageous offer, selected on the basis of the best quality / price ratio, is assessed on the basis of objective criteria related to the subject of the contract. Within these criteria, the cost of use and maintenance also relates to the consumption of energy and natural resources, to polluting emissions and to overall costs, including external ones and to mitigate the impacts of climate change, referring to the entire life cycle of the work, good or service, with the strategic objective of a more efficient use of resources and a circular economy that promotes environment and employment.

2. EMBODIED ENERGY AND CARBON DIOXIDE EMISSIONS INTO THE ATMOSPHERE

To analyze the energy and environmental impacts we refer to the indicators of embodied energy and embodied carbon, of the materials used in the construction process. For Embodied Energy (EE) we mean the total amount of energy needed throughout the life cycle of the material. The calculation of the EE includes the energy required to extract and process the raw materials of all components and the energy used to transport the finished products to the construction site and assemble them, including the energy inputs necessary for the use phase and maintenance of these components, and finally for their removal and disposal

at the end of their life cycle.
Initially it was thought that the content of Embodied Energy of a building was much lower than the Operational Energy, that is the one used to make it work during its useful life. For this reason, the focus has been on reducing operational energy by improving the energy efficiency of building components.
However, more recent research has shown that this is not always the case: while the consumption of operating energy depends on the occupants of the building, embodied energy does not depend on the users but is "incorporated" into the materials.
With respect to the life expectancy of a building, of 100 years, the durability of the materials they make up is different, the latter being subject to a performance decay involving maintenance and replacement. One could therefore consider the life cycle of the individual products, but knowing the useful life of each product and estimating the maintenance times of the products is not a simple operation.
Despite these uncertainties, the durability of a material is a useful indicator of sustainability because durable materials have the potential to dilute the impacts caused to produce them over time. The only possibility is to estimate building duration scenarios by analyzing and comparing consumption during construction and energy consumption in its management phase. This can, for example, make it possible to evaluate the return times of the energy investment in the construction of the building.
The analysis of the time of return of energy consumption spent in the construction phase of the building should be directly proportional to the useful life of the same, since it is expected that materials with high embodied energy will last longer to "recover" the initial energy investment.

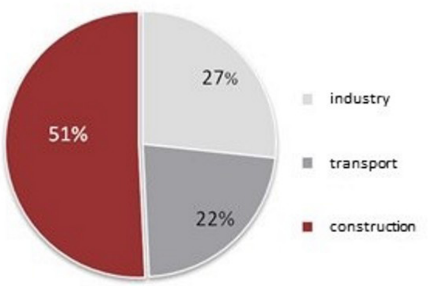


Figure 1
Diagram of the carbon dioxide emission of the various productive sectors (source: https://tecnabita.weebly.com/ecosostenibilitagrave.html)

2.1 EMBODIED ENERGY: SUSTAINABILITY INDICATOR

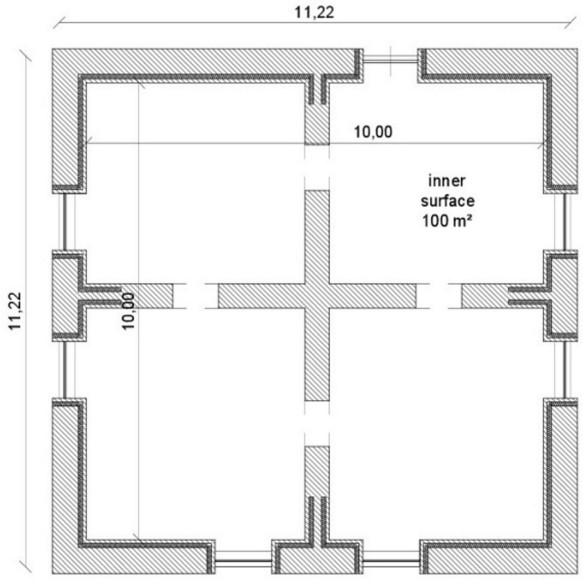
The embodied energy (EE) can be defined as an objective and quantitative indicator that allows to evaluate the environmental pressure of a material, component and / or system. The EE conditions aspects related to the environmental impact of building, in terms of depletion of non-renewable resources, of greenhouse gas emissions, of environmental degradation and reduction of biodiversity, through a series of categories of environmental impacts: greenhouse effect, global warming potential (GWP) (g CO^2); thinning of the ozone layer (g CFC11); acidification (g SO^2); eutrophication (g NO^3); consumption of non-renewable resources: oil (Mtep).
The EE can therefore be considered an indicator of the sustainability of building materials, building systems or buildings as a whole. In general, products that have a greater embodied energy involve high environmental impacts, in particular related to the emissions of greenhouse gases resulting from energy consumption.

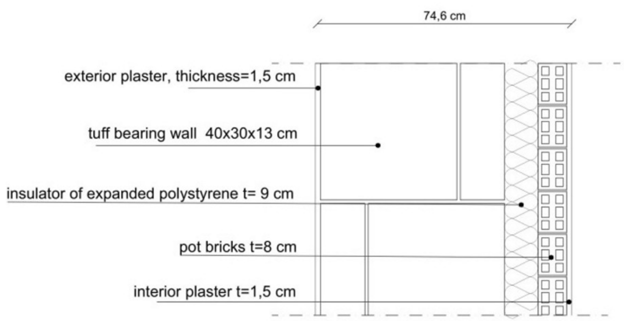
2.2 EMBODIED CARBON: INDICATOR FOR THE EVALUATION OF CO^2 EMISSIONS

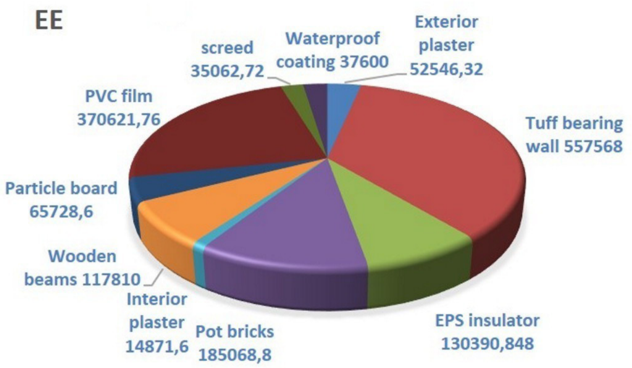
The embodied carbon (EC) is defined as the amount of CO^2 emissions due to the extraction of raw materials, transport, processing, production and other related activities.
The main source of CO^2 emissions, related to the life cycle of building materials, is the combustion of fossil energy sources during the production process. The carbon dioxide embedded in building materials can therefore be determined by knowing quantities and sources of energy consumed and not renewable.
Also for the EC it is necessary to extend the evaluation to the whole life cycle of the material in order not to risk to obtain partial evaluations.

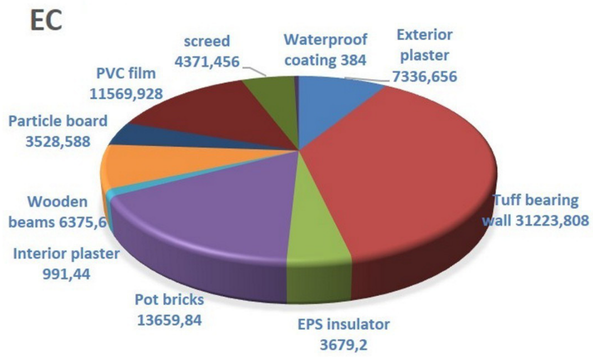
3. METHODOLOGICAL APPROACH AND FORMULATION OF THE MODEL

The present study aimed to investigate the response of the most used building systems in the construction industry, with respect to the environmental requirements of the Italian Procurement Code, preventing the identification and quantification of environmental impact thresholds. We therefore distinguish two construction systems that differ in terms of the assembly principle, namely the 'wet' construction system and the 'dry' construction system. The first type includes, for example, traditional stone masonry and buildings with reinforced concrete structure and traditional infill panels; in the second type we find buildings with prefabricated and / or semi-prefabricated elements, with a wooden or metal bearing structure.
The evaluation model was calibrated on the basis of four technological solutions, two for wet systems and two for dry systems, verifying the behavior of each of them with respect to the end-of-life phase (assuming a life span of 100 years and periodic maintenance). For the elaboration of the model, the database contained in the ICE Inventory of Carbon & Energy summary, elaborated by the University of Bath (England) in 2011, is used, which shows the values of the incorporated energy and the corresponding carbon dioxide emissions of the most used materials in construction and industry.









BUILDING ELEMENTS	MATERIALS	EMBODIED ENERGY [MJ/kg]	EMBODIED CARBON [$kgCO^2$/kg]	EE PER MATERIAL [MJ]	EC PER MATERIAL [$kgCO^2$]
External building					
envelope	*Exterior plaster*	*5,3*	*0,74*	*52546,32*	*7336,656*
	Tuff bearing wall	*1*	*0,056*	*55768*	*31223,808*
	EPS insulator	*88,6*	*2,5*	*102481,848*	*2891,7*
	Pot bricks	*8,4*	*0,62*	*185068,8*	*13659,84*
	Interior plaster	*1,8*	*0,12*	*14871,6*	*991,44*
Plankings	*Wooden beams*	*8,5*	*0,46*	*78540*	*4250,4*
	Particle board	*9,5*	*0,51*	*42453,6*	*2279,088*
	PVC film	*77,2*	*2,41*	*239381,76*	*7472,928*
	Screed (subfloor)	*0,77*	*0,096*	*19662,72*	*2451,456*
Flat roof	*Wooden beams*	*8,5*	*0,46*	*39270*	*2125,2*
	Particle board	*9,5*	*0,51*	*23275*	*1249,5*
	PVC film	*77,2*	*2,41*	*131240*	*4097*
	EPS insulator	*88,6*	*2,5*	*27909*	*787,5*
	Screed	*0,77*	*0,096*	*15400*	*1920*
	Bituminous waterproof coating	*47*	*0,48*	*37600*	*384*

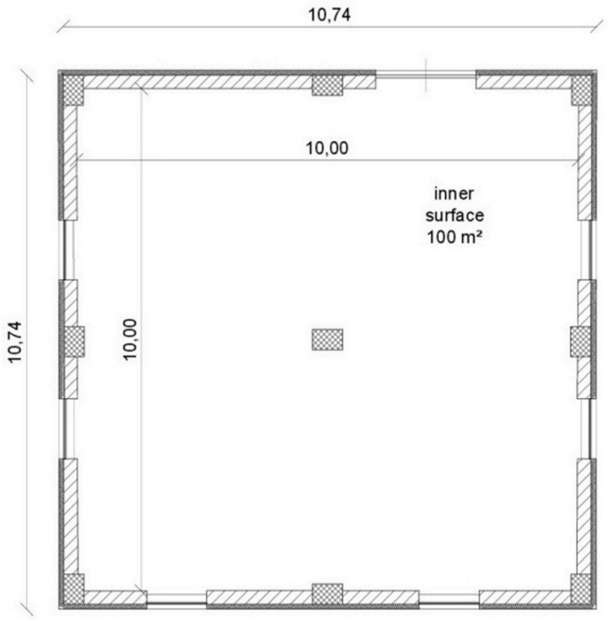
Table 1
Model M1: determination of the values of Embodied Energy and Embodied Carbon for functional units, relative to structural components (structure in elevation, casing, horizontal structures)

TOTAL EE [MJ]	*TOTAL EC per functional unit [kgCO2/m²]*
1567268,648	*216,86*

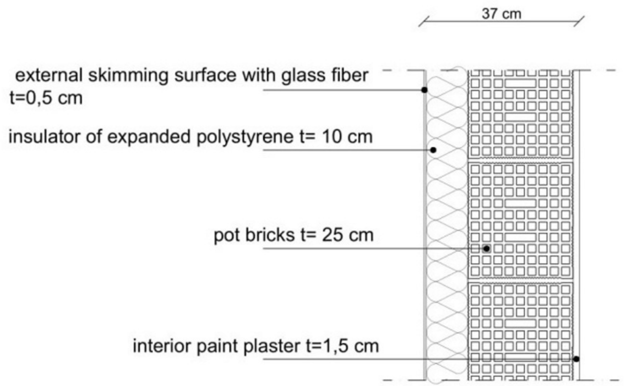
EE per functional unit [MJ/m²]	
	5224,228827

Figure 2
Model M1: traditional masonry structure in stone material; single-warp wooden floors; flat roof (plan and construction detail)

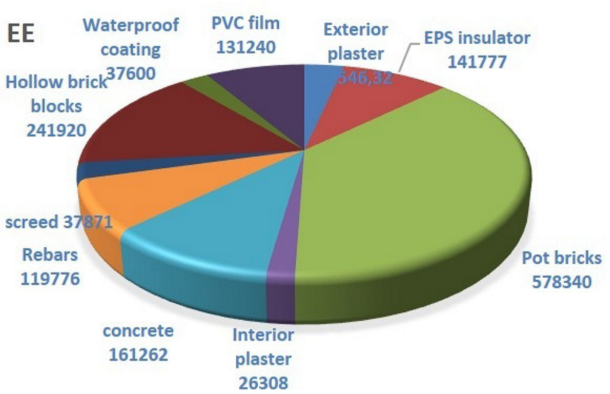
Figure 3
Model M1: diagram on incidence of Embodied Energy (EE) and diagram on incidence of Embodied Carbon (EC) of the materials used.



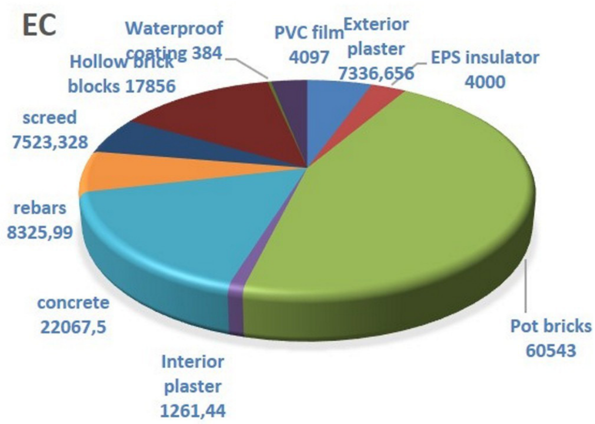
10,74
10,00
inner
surface
100 m²
10,74
10,00



37 cm
external skimming surface with glass fiber
t=0,5 cm
insulator of expanded polystyrene t= 10 cm
pot bricks t= 25 cm
interior paint plaster t=1,5 cm



EE
Waterproof
coating
37600
PVC film
131240
Exterior
plaster
546,32
EPS insulator
141777
Hollow brick
blocks
241920
screed 37871
Rebars
119776
concrete
161262
Interior
plaster
26308
Pot bricks
578340



EC
Waterproof
coating 384
PVC film
4097
Exterior
plaster
7336,656
EPS insulator
4000
Hollow brick
blocks 17856
screed
7523,328
rebars
8325,99
concrete
22067,5
Interior
plaster
1261,44
Pot bricks
60543

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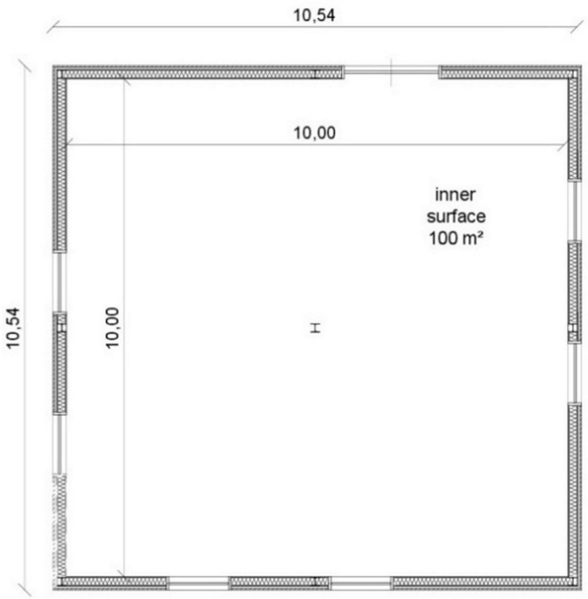
BUILDING ELEMENTS	MATERIALS	EMBODIED ENERGY [MJ/kg]	EMBODIED CARBON [kgCO^2/kg]	WEIGHT [kg]	EE PER MATERIAL [MJ]	EC PER MATERIAL [kgCO^2]
	External building					
envelope	*Exterior plaster*	*5,3*	*0,74*	*9914,4*	*52546,32*	*2,90228*
	EPS insulator	*88,6*	*2,5*	*1285,2*	*113868,72*	*3213*
	Pot bricks	*8,4*	*0,62*	*68850*	*578340*	*42687*
	Interior plaster	*1,8*	*0,12*	*8262*	*14871,6*	*991,44*
Supporting structure	*Concrete pillars*	*0,95*	*0,13*	*47250*	*44887,5*	*6142,5*
	Rebars for pillars	*24,6*	*1,71*	*1701*	*41844,6*	*2908,71*
	Concrete beams	*0,95*	*0,13*	*72000*	*68400*	*9360*
	Rebars for beams	*24,6*	*1,71*	*3168*	*77932,8*	*5417,28*
Plankings	*Screed*	*0,77*	*0,096*	*29184*	*22471,68*	*2801,664*
	Concrete slab	*0,95*	*0,13*	*16500*	*15675*	*2145*
	Concrete beams	*0,95*	*0,13*	*16000*	*15200*	*2080*
	Hollow brick blocks	*8,4*	*0,62*	*19200*	*161280*	*11904*
	Interior plaster	*1,8*	*0,12*	*4104*	*7387,2*	*492,48*
Flat roof	*Bituminous waterproof coating*	*47*	*0,48*	*800*	*37600*	*384*
	Screed	*0,77*	*0,096*	*20000*	*15400*	*1920*
	EPS insulator	*88,6*	*2,5*	*315*	*27909*	*787,5*
	PVC film	*77,2*	*2,41*	*1700*	*131240*	*4097*
	Concrete beams	*0,95*	*0,13*	*8000*	*7600*	*1040*
	Concrete slab	*0,95*	*0,13*	*10000*	*9500*	*1300*
	Hollow birck blocks	*8,4*	*0,62*	*9600*	*80640*	*5952*
	Interior plaster	*1,8*	*0,12*	*2250*	*4050*	*270*

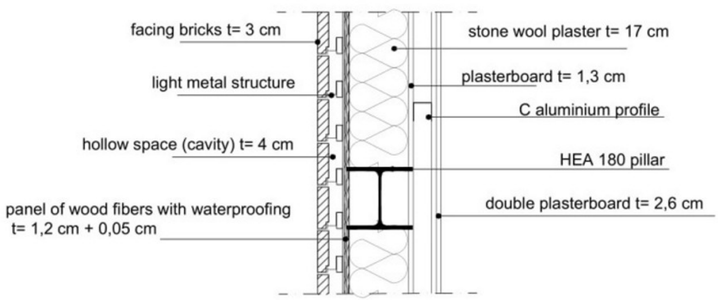
TOTAL EE [MJ]	*TOTAL EC per functional unit [kgCO2/m²]*
1528644,42	*352,99*
EE per functional unit [MJ/m²]	
	5095,4814

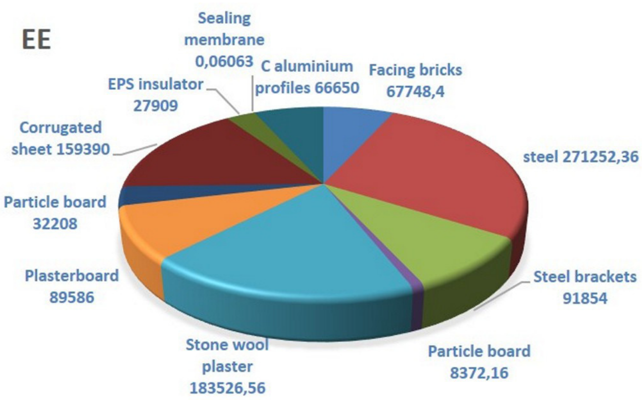
Figure 4
Model M2: structure frame framed in concrete with traditional infill; cement-based floor slab, lightened with perforated bricks; flat roof (plan and construction detail)

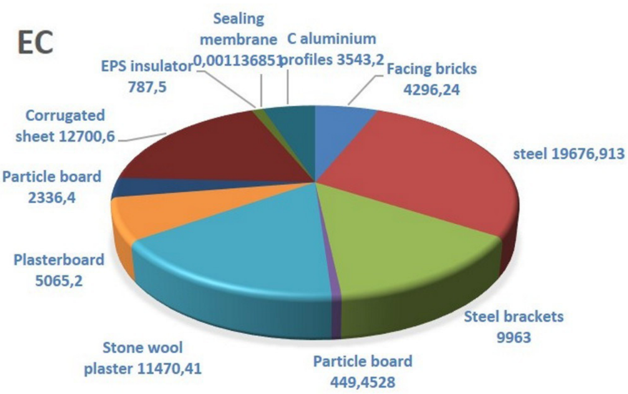
Figure 5
Model M2: diagram on incidence of Embodied Energy (EE) and diagram on incidence of Embodied Carbon (EC) of the materials used.

Table 2
Model M2: determination of the values of Embodied Energy and Embodied Carbon for functional units, relative to structural components (structure in elevation, casing, horizontal structures)


10,54
10,00
inner
surface
100 m²
10,54
10,00


facing bricks t= 3 cm
light metal structure
hollow space (cavity) t= 4 cm
panel of wood fibers with waterproofing
t= 1,2 cm + 0,05 cm
stone wool plaster t= 17 cm
plasterboard t= 1,3 cm
C aluminium profile
HEA 180 pillar
double plasterboard t= 2,6 cm


EE
Sealing
membrane
0,06063
C aluminium
profiles 66650
Facing bricks
67748,4
EPS insulator
27909
Corrugated
sheet 159390
steel 271252,36
Particle board
32208
Plasterboard
89586
Steel brackets
91854
Stone wool
plaster
183526,56
Particle board
8372,16


EC
Sealing
membrane
0,001136851
C aluminium
profiles 3543,2
EPS insulator
787,5
Facing bricks
4296,24
Corrugated
sheet 12700,6
steel 19676,913
Particle board
2336,4
Plasterboard
5065,2
Steel brackets
9963
Stone wool
plaster 11470,41
Particle board
449,4528

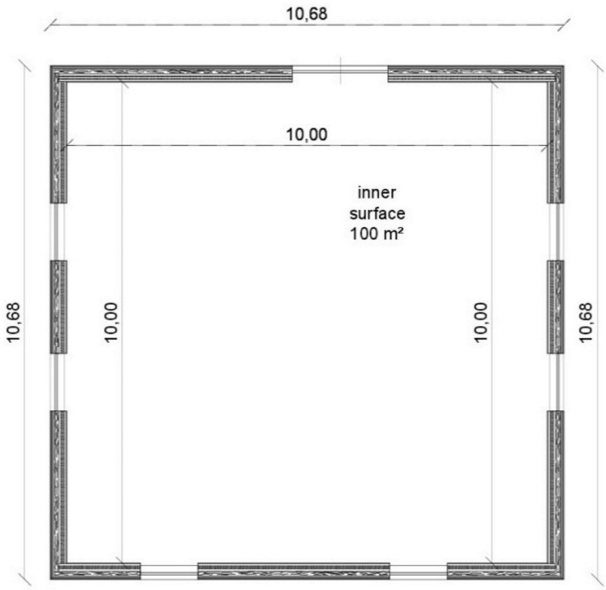
BUILDING ELEMENTS	MATERIALS	EMBODIED ENERGY [MJ/kg]	EMBODIED CARBON [kgCO^2/kg]	EE PER MATERIAL [MJ]	EC PER MATERIAL [kgCO^2]
External building					
envelope	*Facing bricks*	*8,2*	*0,52*	*67748,4*	*4296,24*
	Steel brackets	*56,7*	*6,15*	*91854*	*9963*
	Sealing membrane	*47*	*0,48*	*0,06063*	*0,001136851*
	Particle board	*9,5*	*0,51*	*8372,16*	*449,4528*
	Stone wool plaster	*16,8*	*1,05*	*183526,56*	*11470,41*
	C aluminium profiles	*155*	*8,24*	*66650*	*3543,2*
	plasterboard	*6,75*	*0,38*	*174960*	*9849,6*
Supporting structure	*Steel pillars*	*24,4*	*1,77*	*77958*	*5655,15*
	Steel beams	*24,4*	*1,77*	*82569,6*	*5989,68*
	Steel connections	*24,4*	*1,77*	*16052,76*	*1164,483*
	Steel braces	*24,4*	*1,77*	*46360*	*3363*
Plankings	*Particle board*	*9,5*	*0,51*	*36388,8*	*1953,504*
	Rebars for beams	*24,4*	*1,77*	*32208*	*2336,4*
	Plasterboard (drywall)	*1,8*	*0,12*	*3841,344*	*256,0896*
	Corrugated sheet	*31,5*	*2,51*	*110250*	*8785*
Flat roof	*Steel beams*	*24,4*	*1,77*	*16104*	*1168,2*
	Corrugated sheet	*31,5*	*2,51*	*49140*	*3915,6*
	EPS insulator	*88,6*	*2,5*	*27909*	*787,5*
	Plasterboard (drywall)	*1,8*	*0,12*	*2106*	*140,4*

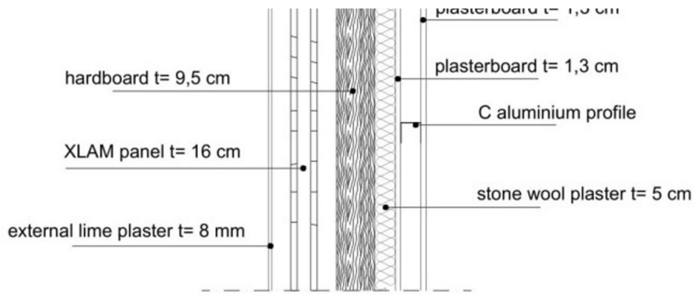
TOTAL EE [MJ]	*TOTAL EC per functional unit [kgCO2/m²]*
1093998,685	*250,29*
EE per functional unit [MJ/m²]	
	3646,662282

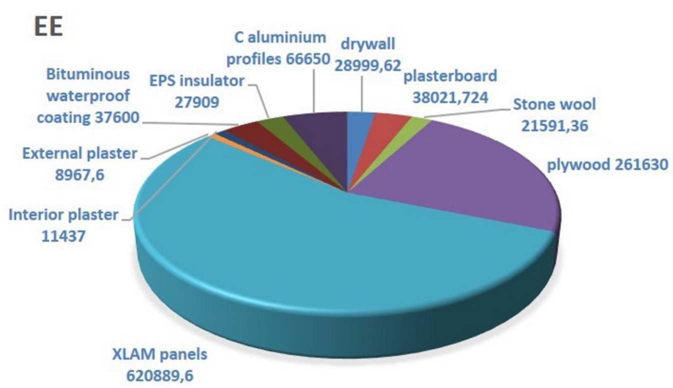
Table 3
Model M3: determination of the values of Embodied Energy and Embodied Carbon for functional units, relative to structural components (structure in elevation, casing, horizontal structures)

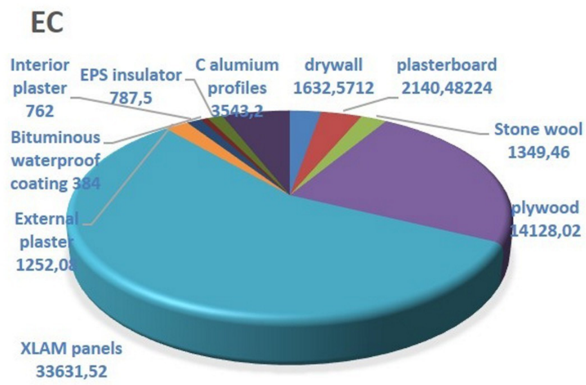
Figure 6
Model M3: supporting structure of HEA 180 pillars and IPE 180 beams and bracing in UPN 120 profiles; floors with IPE 80 joists and corrugated sheet interposed to the wooden plank; flat roof flat roof (plan and construction detail)

Figure 7
Model M3: diagram on incidence of Embodied Energy (EE) and diagram on incidence of Embodied Carbon (EC) of the materials used.


10,68
10,00
inner
surface
100 m²
10,68
10,00
10,00
10,68


hardboard t= 9,5 cm
plasterboard t= 1,3 cm
C aluminium profile
XLAM panel t= 16 cm
stone wool plaster t= 5 cm
external lime plaster t= 8 mm


EE
C aluminium profiles 66650
drywall 28999,62
plasterboard 38021,724
Bituminous waterproof coating 37600
EPS insulator 27909
Stone wool 21591,36
External plaster 8967,6
plywood 261630
Interior plaster 11437
XLAM panels 620889,6


EC
Interior plaster 762
EPS insulator 787,5
C alumium profiles
drywall 1632,5712
plasterboard 2140,48224
Stone wool 1349,46
Bituminous waterproof coating 384
plywood 14128,02
XLAM panels 33631,52

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BUILDING ELEMENTS	MATERIALS	EMBODIED ENERGY [MJ/kg]	EMBODIED CARBON [kgCO²/kg]	EE PER MATERIAL [MJ]	EC PER MATERIAL [kgCO²]
External building					
envelope	*Plasterboard (drywall)*	*6,75*	*0,38*	*28999,62*	*1632,5712*
	C aluminium profiles	*155*	*8,24*	*66650*	*3543,2*
	plasterboard	*6,75*	*0,38*	*38021,724*	*2140,48224*
	Stone wool	*16,8*	*1,05*	*21591,36*	*1349,46*
	plywood	*15*	*0,81*	*261630*	*14128,02*
	XLAM panel	*12*	*0,65*	*282009,6*	*15275,52*
	External lime plaster	*5,3*	*0,74*	*8967,6*	*1252,08*
Plankings	*Wooden beams*	*12*	*0,65*	*218880*	*11856*
	Particle board	*1,8*	*0,12*	*7387,2*	*492,48*
Flat roof	*Bituminous waterproof coating*	*47*	*0,48*	*37600*	*384*
	XLAM panel	*12*	*0,65*	*120000*	*6500*
	EPS insulator	*88,6*	*2,5*	*27909*	*787,5*
	Interior plaster	*1,8*	*0,12*	*4050*	*270*

Table 4
Model M4: determination of the values of Embodied Energy and Embodied Carbon for functional units, relative to structural components (structure in elevation, casing, horizontal structures)

TOTAL EE [MJ]	*TOTAL EC per functional unit [kgCO2/m²]*
1123696,104	*198,70*
EE per functional unit [MJ/m²]	
	3745,65368

Figure 8
Model M4: load-bearing structure, floors and roofing in XLAM wooden panels; flat roof (plan and construction detail)

Figure 9
Model M4: diagram on incidence of Embodied Energy (EE) and diagram on incidence of Embodied Carbon (EC) of the materials used.

4. MODEL VERIFICATION: CASE STUDIES

For the verification of the model two works of contemporary architecture have been identified, located within the Campus of Fisciano of the University of Salerno, Italy.

The first case study (C1), which concerns University Residences, is representative of the 'wet' technological system, as its supporting structure is a reinforced concrete framework. Specifically, a single square block of 13.5 meters has been analyzed. It is necessary to clarify that, since the building was designed before the application of the energy certification legislation, it has not been foreseen the presence of insulation inside the wrapping package. Therefore, in order to make the case study comparable with the theoretical reference model (M2), an energy adjustment has been assumed (in compliance with the minimum requirements as per Ministerial Decree 26/06/2015) by applying polystyrene beads for insufflation. inside the existing inner tube.

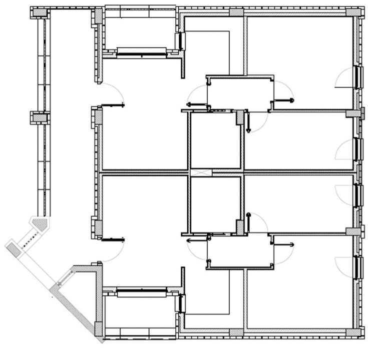
The second case study (C2), to be compared with the theoretical reference model (M3), concerns the L7 building, home to university laboratories. The latter, built with a steel framed structure, has been designed and manufactured in compliance with the LEED sustainability protocol (Platinum class).

Figure 10
Case Study C1: Residences University, Campus di Fisciano, University of Salerno, Italy

Figure 11
Spin Off Laboratories L7 Campus di Fisciano, University of Salerno, Italy

4.1 UNIVERSITY RESIDENCES (C1)

Start of work: 2006
Works completion: 2013
Prevalent Structure: Reinforced concrete
Client: University of Salerno
Construction company ATI: IGER s.r.l ;. General Construction s.r.l .; Impianti s.r.l.
Production cost: 14000000
Status: Works realized
Typology: University / student residences



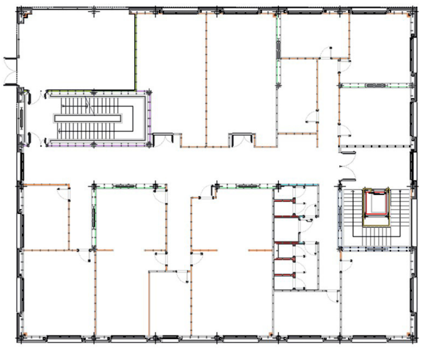
BUILDING ELEMENTS	MATERIALS	WEIGHT	EE PER MATERIAL	EC PER MATERIAL
External building				
envelope	*Pot bricks*	*36634,5*	*307729,8*	*22713,39*
	Facing red bricks	*43819,2*	*359317,44*	*22785,984*
	Polystyrene beads	*1481,55*	*131265,33*	*3703,875*
Supporting structure	*Concrete for pillars*	*86400*	*82080*	*11232*
	Rebars for pillars	*3110,4*	*76515,84*	*5318,784*
	Concrete for beams	*157800*	*149910*	*20514*
	Rebars for beams	*1735,8*	*42700,68*	*2968,218*
Plankings	*Screed*	*61200*	*47124*	*5875,2*
	Concrete slab	*61200*	*58140*	*7956*
	Concrete beams	*20800*	*19760*	*2704*
	Pot bricks	*24960*	*209664*	*15475,2*
	Interior plaster	*13770*	*24786*	*1652,4*
Flat roof	*Gravel*	*153000*	*275400*	*18360*
	Bituminous waterproof coating	*13600*	*639200*	*6528*
	Screed	*51000*	*39270*	*4896*
	Bituminous felt paper	*11220*	*527340*	*5385,6*
	Thermal insulation in polystyrene	*3570*	*316302*	*8925*
	Vapour barrier membranes	*5100*	*423810*	*9894*

TOT ALWEIGHT	*TOTAL EE*	*EE per FUNCTIONAL UNIT*
750401,45	*3548811,69*	*376,36*
	EE per functional unit	
	7544,242538	

Table 5
Case study 1: determination of the values of Embodied Energy and Embodied Carbon for functional units, relative to structural components (structure in elevation, casing, horizontal structures)

4.2 L7 SPIN OFF LABS (C2)

Completion of works: 2014
Prevalent Structure: Steel
Client: University of Salerno
Intended use: University laboratories
Construction company: AMES S.p.a.
Status: Works realized
Typology: University laboratories



BUILDING ELEMENTS	MATERIALS	WEIGHT	EE PER MATERIAL	EC PER MATERIAL
External building				
envelope	*Alucobond panels*	*1535,82*	*178308,702*	*8170,5624*
	Polyurethane sandwich panel	*134,0352*	*9663,93792*	*402,1056*
	Galvanized steel structure	*12168*	*474552*	*34313,76*
	Panel in gypsum plate	*26527,8*	*179062,65*	*10080,564*
	Stone wool panel	*29320,2*	*492579,36*	*30786,21*
	Gypsum plasterboard	*2652,78*	*17906,265*	*1008,0564*
Supporting				
Plankings	*Steel pillars*	*18404,1*	*449060,04*	*32575,257*
	Steel trussess	*16555,5*	*403954,2*	*29303,235*
	Beams	*9363,12*	*228460,128*	*16572,7224*
	Corrugated sheet	*21140,34*	*515824,296*	*37418,4018*
	Concrete slab	*6775,75*	*6436,9625*	*880,8475*
	Heel plates and e bolts for connections (10% of the total weight)	*6546,306*	*159729,8664*	*11586,96162*
Flat roof	*Concrete floor*	*466590,6*	*396602,01*	*65322,684*
	Double bituminous membrane	*59249,6*	*2784731,2*	*28439,808*
	Screed	*185155*	*142569,35*	*17774,88*
	polyurethane panel	*1777,488*	*128156,8848*	*5332,464*

TOTAL EE [MJ]	*EC per functional unit [kgCO2/m²]*
6567597,853	*237,05*

EE per functional unit [MJ/m²]	
	4718,101906

Table 6
Case study 2: determination of the values of Embodied Energy and Embodied Carbon for functional units, relative to structural components (structure in elevation, casing, horizontal structures)

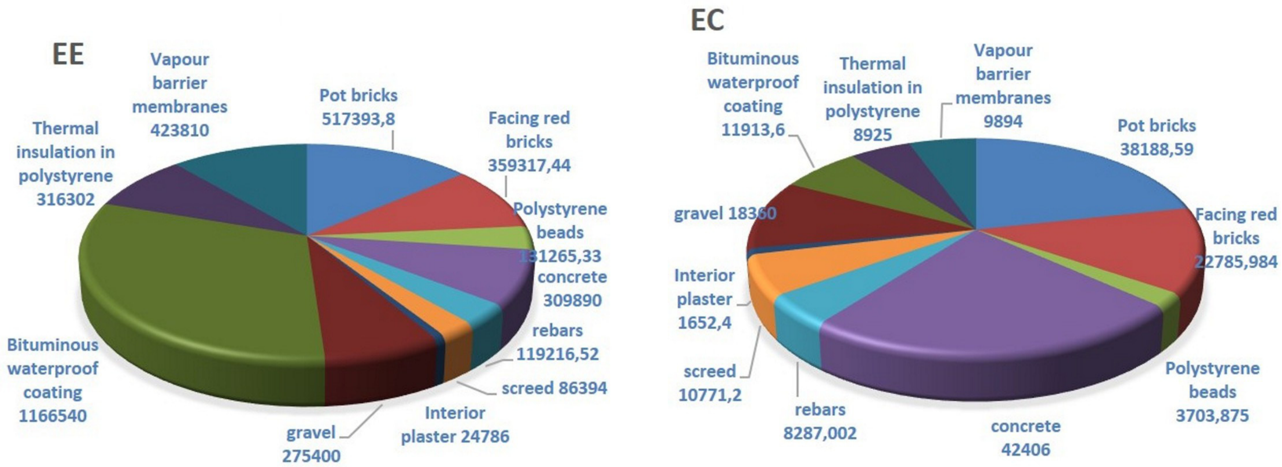


Figure 10
Case study C1 diagram on incidence of Embodied Energy (EE) and diagram on incidence of Embodied Carbon (EC) of the materials used.

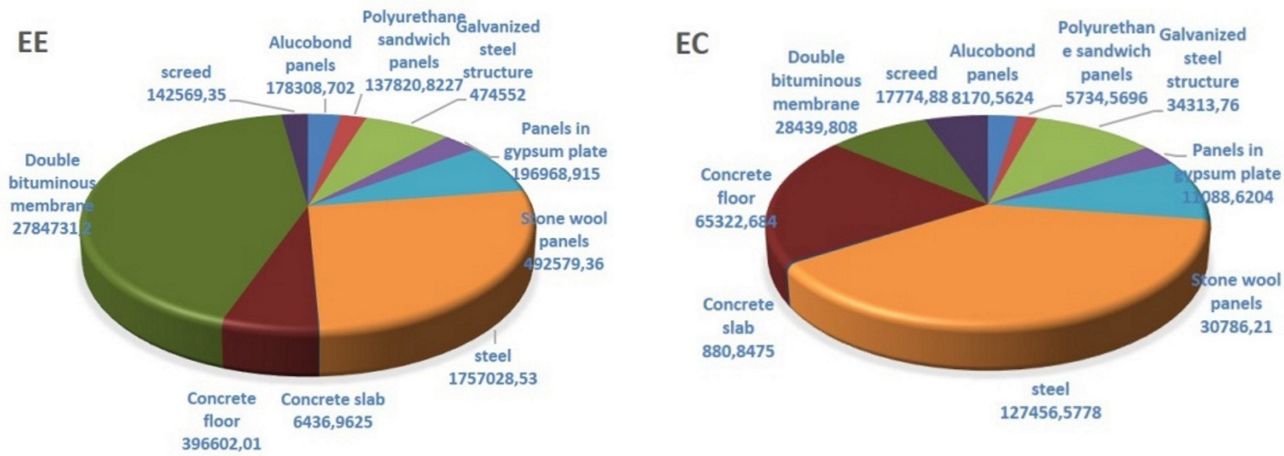


Figure 11
Case study C2 diagram on incidence of Embodied Energy (EE) and diagram on incidence of Embodied Carbon (EC) of the materials used.

5. DISCUSSION OF RESULTS

The following histograms show the comparison between the values of EE and EC of the four models (M1, M2, M3, M4) and of the case studies (C1, C2). With regard to Embodied Energy, "wet" systems (M1, M2) have higher values than "dry" construction systems (M3, M4). Both case studies (C1, C2) have higher EE values than the thresholds defined by the reference models (M2 for case C1 and M3 for case C2).
As far as carbon dioxide emissions are concerned, the highest value appears to be that relating to the case study C1; the models M1, M3, M4 have lower values than the M2 model. In this case, the most virtuous model appears to be the one with a wooden structure (M4). The values relating to the models are still acceptable; the values of carbon dioxide emissions of the two case studies do not differ from the values of the models with the same type of construction.

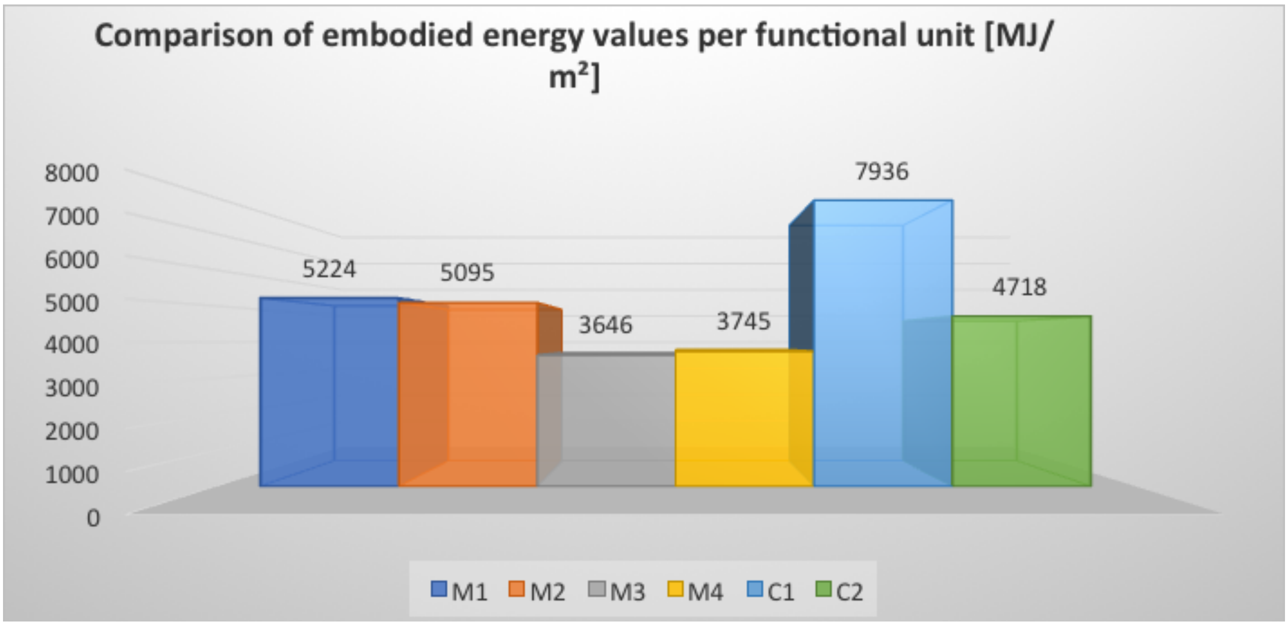
Figure 12
Histograms for comparing the values of Embodied Energy between the simulated models (M1, M2, M3, M4) and the case studies (C1, C2)

5.1 DISCUSSION OF THE RESULTS RELATED TO THE CASE STUDY C1

The comparison between the case study C1 and the threshold values of the reference model (M2) shows a worse behavior of the case study, validating the effectiveness of the values defined for the model M2.

5.2 DISCUSSION OF THE RESULTS RELATED TO THE CASE STUDY C2

The comparison between the case study C2 and the threshold values of the Reference Model (M3) shows higher values of EE and lower EC values of the case study, compared to the values defined for the M3 model. This circumstance is due to the fact that the chosen case study was carried out according to the parameters of the LEED sustainability protocol. Thus, in an overall assessment between the thresholds of EE and EC, the model M3, as described, is considered valid. The summary diagrams (figs.14-15) show that appropriate design choices can lead to a 51% reduction in the EE and a 69% reduction in emissions (EC).



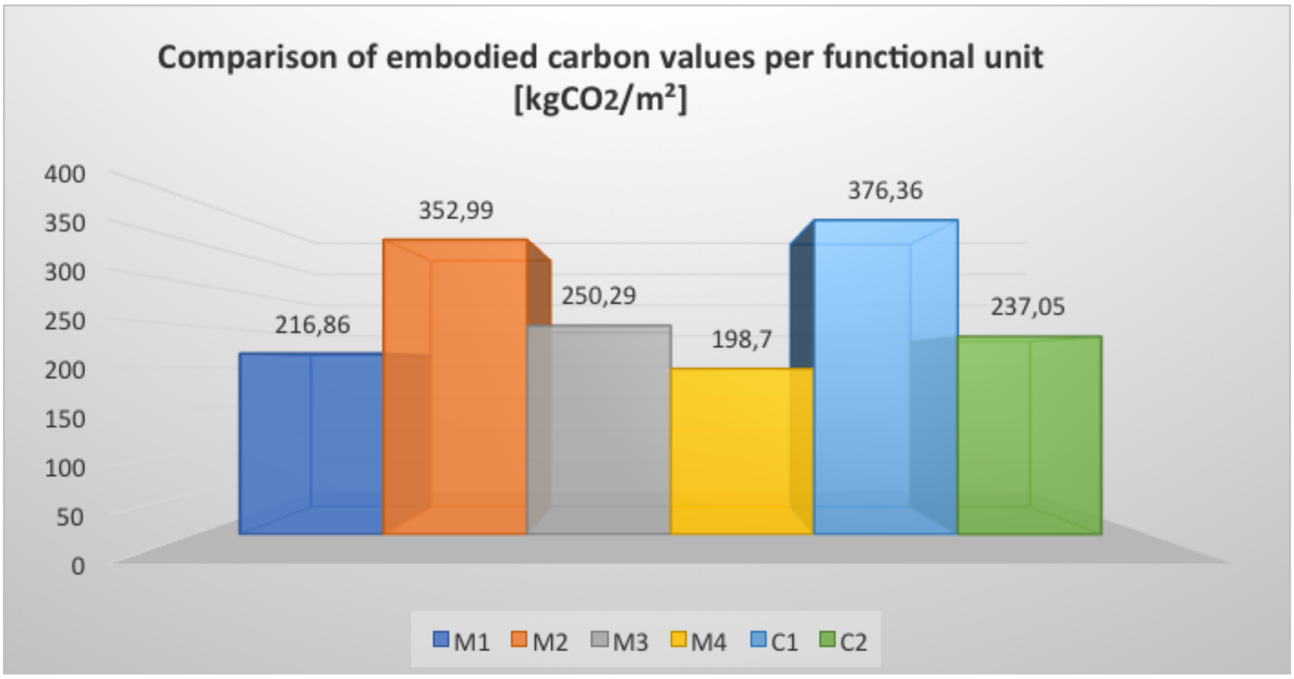


Figure 13
Histograms for comparing the values of Embodied Carbon between the simulated models (M1, M2, M3, M4) and the case studies (C1, C2)

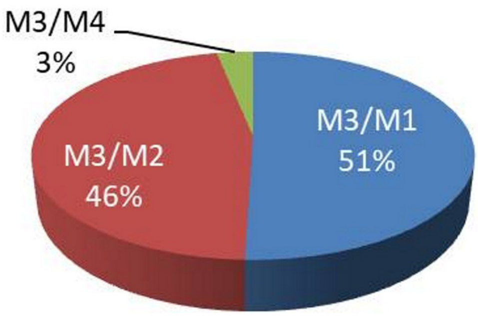


Figure 14
Percentage reduction of the virtuous model (M3) compared to the other models (for EE content, expressed in MJ / m2)

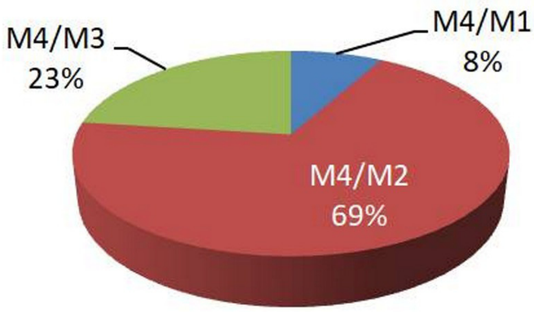


Figure 15
Percentage reduction of the virtuous model (M4) compared to the other models (for EC content, expressed in kgCO² / m²)

5. CONCLUSIONS

In Italy, the reinforced concrete construction system, especially in the second half of the 20th century, had a notable diffusion with regard to dry construction technologies, which instead became more widespread in Northern Europe and America. Compared to traditional ('wet') construction systems that provide prevailing work on site, the dry system represents a concrete and effective response to the needs of environmental sustainability, in accordance with the principles of the Green Building.
Furthermore, the dry construction system offers a series of advantages, such as:

- the reduction in execution times, with a significant reduction in the overall duration of the works and consequent economic savings;
- the improvement of the quality of the final work, being the same made with pre-formed and pre-shaped components, as well as tested in the workshop;
- the improvement of the safety conditions on construction sites as the reduction in the duration of the work and the reduction of many 'on-site' processes, entails a consequent reduction of workers' risk exposure.

Despite not having carried out an economic analysis for the definition of the model, however, a survey was carried out in the literature: contemporary scientific research, highlighting the need to compensate for an evident productive gap between the construction industry and the mainly production industries serial, strongly hopes, for this sector, the adoption of the off-site construction process.
It has been estimated that "in construction, half of the hours worked does not generate economic value. It is shared opinion that the production hemorrhage of the sector can be stopped opting for a hybridization with the manufacturing sec-tor. Nowadays, the synthesis of construction and production is identified with the off-site building. It lowers the intensity of the construction work on site by transferring it to the laboratory, where the components are built on the basis of economic principles that align those of industrial production" (Nesticò, Moffa, 2018). Already in 2010, in the United States, a committee composed of the National Institute of Standards and Technology (NIST) and the National Research Council (NRC), believed that greater use and deployment of these techniques (if used appropriately) it would have resulted in lower project costs, shorter programs, better quality.
The results obtained by the present study also highlight another type of consideration: design choices addressed towards the use of 'dry' con-struction systems, contribute to further reducing environmental pressures, through a further re-duction of the incorporated energy, in the per-spective of a possible second life cycle of the building component (setting as invariant the structural and functional integrity of the building component). In fact, the summary ICE Inventory of Carbon & Energy, used as a tool for the definition of the model, provides a substantial reduction of the energy rate incorporated between the primary raw material (primary) and the so-called secondary or recycled (secondary) material. The final consideration, therefore, is that buildings made with secondary materials will have extremely reduced environmental impacts compared to those made with virgin raw materials.
The results also indicated design scenarios that are oriented towards the use of construction sys-tems that present advantages in terms of disassembly, recovery and reuse of the various components; in addition to the attitude of such sys-tems, to be resilient, or to be able to be adapted and transformed during the life cycle of the building organism.

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