

CARBON STORED BY FURNISHING WOOD-BASED PRODUCTS: AN ITALIAN CASE STUDY

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ABSTRACT

The concentration of atmospheric carbon dioxide is constantly rising, with severe effects on global climate change. To mitigate impacts of climate change, the role of forest in terms of carbon sequestration are well-known as trees naturally pull CO₂ from the atmosphere as they grow. Contrarily, only recently the carbon mitigation value of wood-based products in buildings has been recognized.

Buildings are a fundamental sector for wood-based products, both in terms of volume and service life length. In particular, furnishings in housing include high quantities of wood-based products; they are usually made, partly or entirely, by solid wood or by wood-based panels such as plywood, particleboard and medium density fiberboard. These wood furnishings store biogenic carbon during their service life. In this context, the present study investigated the amount of carbon stored by furnishing wood-based products for an apartment in Torino, Italy. The overall amount, determined according to European Standard, resulted in 3531 kg of CO₂-equivalents stored. This corresponds to 45,8 kg/m² of indoor walkable area; simulating lower and higher intensity usages of wood-based products provided carbon storage values of 35,1 and 55,3 kg/m², respectively.

On the whole, the present study gave an order of magnitude of the role played in carbon storage by furnishing wood-based products in building and illustrates their relevance in mitigating climate change.

Keywords: Building, carbon mitigation value, climate change, furnishing, wood.

INTRODUCTION

Climate change is one of the main environmental challenges that modern society faces. Climate change impacts are strongly affecting the entire planet and, to mention some, include extensive droughts, catastrophic forest fires, melting of glaciers and extreme weather events (Hansen *et al.* 1981, Pachauri *et al.* 2014, Houghton 2015).

Anthropogenic greenhouse gas (GHG) emissions are the primary cause of climate change with land use changes and combustion of fossil fuels being the main source of emissions. Atmospheric carbon dioxide (CO₂) is one of the most important GHG both for its role in heating Earth and for the impact that humans have on its concentration (Hansen *et al.* 1981, Anderson *et al.* 2016). Starting from the beginning of the 1900s, the human activity has caused a dramatic increasing in the concentration of atmospheric CO₂ which has recently exceeded 400 ppm and likely to reach 1000 ppm or higher by 2100 unless measures to mitigate GHG emissions are taken (Forster *et al.* 2007, Pachauri *et al.* 2014, SCRIPPS 2018, NOAA 2018).

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Adopting and enhancing CO₂ mitigation strategies are absolutely necessary to limit the global effects of climate change (Friedlingstein *et al.* 2011; Pilli *et al.* 2015). CO₂ mitigation strategies include GHG emissions reduction by using non-CO₂-emitting energy sources (e.g. solar and wind), capturing emitted CO₂ through natural processes of photosynthesis in plants through reforestation and afforestation along with man-made processes, and finally (biogenic) carbon storage via harvested wood products (Thomas 2001, McKinley *et al.* 2011, Lippke *et al.* 2011, Williamson 2016, Geng *et al.* 2017). Through photosynthesis, growing trees absorb carbon dioxide to form their tissues. Once formed, the CO₂ is fixed as biogenic carbon in wood and in the wood-based products (WBPs) made from the wood. The carbon storage lasts until the WBPs are decomposed or burned, releasing CO₂ and other GHGs back to the atmosphere (Bergman *et al.* 2013). The environmental value of forests in terms of carbon sequestration is well-known, while more attention has recently been paid to wood and wood-based products (Bergman *et al.* 2014, Miner *et al.* 2014, Thonemann and Schumann 2016; Vitale and Arena 2018). From the static viewpoint of time, the biogenic CO₂ emissions released during WBP production are more than balanced out from forest carbon uptake during tree growth assuming the forest regrows to its original state. This occurs even if the GHG fluxes from re-sequestering forest carbon occur outside the given time horizon for calculating the impact on climate change which is typically 100 years (Bergman 2012, Salazar and Bergman 2013, IPCC 2014). For a carbon storage frame of reference, in the United States, an average single family house of 233-m² in 2012 contains roughly 22000 oven-dried kg of structural wood elements (Meil *et al.* 2004, McKeever and Elling 2015, McKeever and Elling 2018). Therefore, a 233-m² home could store 11000 kg or about 50 kg/m² of carbon assuming wood carbon content at 50% and excluding adhesives. This value does not include nonstructural wood products, which may have a shorter service life (Smith *et al.* 2006, Skog 2008, Elling and McKeever 2018). Service life of structural wood products tends to match the service life of the structure itself. Therefore, given a median life of 80 years for a single family home (Skog 2008), the stored carbon can last from two to three forest rotation cycles of intensely managed, highly productive forests (O'Connor 2004, Smith *et al.* 2006). Typical single-family houses in the U.S. at 233-m² can be twice as large as housing in Italy (Cannari and Faiella 2008, McKeever and Elling 2015, US Department of Commerce 2017). Thus, also considering the different construction typologies, structural elements of typical Italian single-family houses constructed from wood could store less than 2800 kg of carbon.

The value of carbon storage performed by wood and WBPs mainly depends on density, volume, wood percentage and service life length. The higher the density of wood, the higher the amount of carbon stored in it on a volume basis. For many wood species, carbon constitutes about 50% the weight of wood on an oven-dried basis; this value is commonly used for analyses on carbon storage, even if differences among wooden species exist (Gang *et al.* 2017, EN 16449:2014, Thomas and Martin 2012). Secondly, everything else being equal, a higher volume of furnishing WBPs means a higher amount of carbon stored. Similarly, a higher percentage of wood in a WBP, in case where the product is not entirely made by solid wood, means a higher carbon storage value for a given volume. This applies both to semi-finished and finished products; for instance, plywood is mostly wood but part resin.

Finally, a longer service life of WBPs determines a longer, and thus more valuable, storage period because this keeps the carbon in the wood in a stable carbon pool. Correspondingly, finding the half-life of individual furnishing WBPs can be difficult to find but Smith *et al.* (2006) estimated the half-life of U.S. household furniture at 30 years. Any efforts to increase the half-life would increase pool of carbon storage in WBPs thus reducing carbon (i.e. GHG) emissions in the atmosphere.

The amount of WBPs used in building can reach very high levels depending on housing types. Their service life length is also often relevant, since wooden products usually remain in buildings for decades and even centuries especially structural elements (Aktas *et al.* 2012, Takano *et al.* 2015). Recently, the building sector has paid an increasing attention to the environmental aspects and their interest in WBPs has grown because of wood's unique ecological profile (Ramage *et al.* 2017, Theoman *et al.* 2010, Resch 2008). WBPs can be divided in two categories: structural (i.e. framing lumber, panel products, solid wood beams, cross laminated limber, etc.) and non-structural (i.e. furniture, flooring, doors and windows etc.).

In this context, the present paper investigated the amount of carbon stored by non-structural WBPs in a furnished apartment located in Torino, Italy. The furnishings selected for analysis were flooring,

chairs, tables, closets, kitchen furniture, beds and doors. The amount of carbon stored was determined according to the calculation method provided by EN 16449:2014. The (base-case) furnished apartment was considered as a ‘mid-intensity’ usage of WBPs as mentioned previously.

The results provided for the first time the magnitude of carbon stored in furnishings for an actual apartment. This enables a better understanding of the relevance of non-structural WBPs used in the building sector.

MATERIALS AND METHODS

The chosen apartment was located in the metropolitan area of Torino in northern Italy. It covers a total walkable area of 88,5 m² (76,7 m² indoor and 11,8 m² outdoor). It is inhabited and included furnishings such as chairs, beds, flooring, doors, etc. (Figure 1 and Table 1). Some furnishings were made of solid wood coming from regional commercial wood species traditionally used in making furnishings, such as sweet chestnut (*Castanea sativa*), European oak (*Quercus petraea*) and European walnut (*Juglans regia*). Other furnishings, instead, are entirely or partly made of wood-based panels (plywood, particleboard and medium density fiberboard (MDF)).

Reference examples of residential furnishing in northern Italy are not available, due to the large amount of variables involved. Anyway, the apartment selected contains the typical furnishings that one can expect in residential housing in this region. For instance, taking student housing as a specific case of residential housing, the furnishings of the apartment are in line with those envisaged by the “rental agreement type” of the City of Padova, northern Italy, for a type apartment to be rented to students (Comune di Padova 2017).



Figure 1: Floor plan of the apartment chosen as a case study. Wood based products are colored in light grey. All furnishings are drawn in scale, except for frames that have been enlarged to be more visible. Baseboard is not shown for easier readability, anyway it is present in each room in which parquet flooring is illustrated. Grey color on windows represents the roller shutter boxes.

Table 1: Furnishings in the apartment: type, position (K: kitchen, L: living room, D: double bed room, S: single room, C: corridor, B: bathroom, BC: balconies, O: overall, W: windows), gross length, width and height, in mm, effective volume of WBPs embedded, in m³, and wood species or WBPs; s3 indicates WBPs added for simulating the scenario 3.

¹Eu: European.

Position, Furnishing	Gross dimensions (hovxh, mm)	WBPs volume (m ³)	Wood species or WBPs ¹	Position, Furnishing	Gross dimensions (hovxh, mm)	WBPs volume (m ³)	Wood species or WBPs
O, parquet	7260x7260x12.5	0,659	birch and Eu oak plywood	S, night table	450x350x380	0,010	particleboard
O, baseboard	45930x10x80	0,037	birch and Eu oak plywood	S, closet	1400x500x2000	0,124	Eu walnut
O, inner doors and frames	800x35x2140	0,195	Scots pine MDF	S, bookcase	1420x250x900	0,026	spruce
O, shutter boxes	1500x400x8	0,085	poplar plywood	D, bed	2000x1800x300	0,080	particleboard beech plywood MDF
O, frames	various	0,006	cherry, spruce MDF	D, night tables	520x380x530	0,040	spruce
L, entry door	900x10x2100	0,019	Eu oak	D, commode	600x370x1110	0,051	spruce
L, TV stand	1800x440x450	0,034	particleboard	D, wardrobe	4270x600x2900	0,556	spruce particleboard
L, shelves	800x250x100 (x4)	0,080	particleboard	K, furniture	4019x600x960	0,407	particleboard
L, bookcase	1000x350x3000	0,110	Eu walnut	K, table	1530x750x770	0,042	sweet chestnut
L, small table	450x450x535	0,004	Eu walnut	K, chairs	460x400x660	0,021	beech
L, showcase	750x300x1650	0,020	sweet chestnut, particleboard	K, closet	760x400x1300	0,045	particleboard
L, chair	440x420x900	0,005	Eu oak	B, sink cabinet	1740x500x500	0,041	particleboard MDF
L, writing desk	880x440x580	0,025	Eu walnut spruce	B, closet	1500x370x2000	0,079	Scots pine MDF
L, couch	2200x600x1250	0,106	particleboard	B, ladder	340x250x1500	0,020	beech
BC, chairs	440x420x900 (x2)	0,010	Scots pine	SCENARIO 3			
BC, table	700x500x515	0,005	Scots pine	O s3, windows and frames	various	0,478	spruce
C, closet	2000x370x2900	0,143	particleboard MDF	O s3, plywood	8760x8760x12.5	0,959	birch and Eu oak plywood
S, bed	2000x900x300	0,031	Scots pine beech plywood	O s3, baseboard	65390x10x80	0,052	birch and Eu oak plywood

Scenarios were developed with scenario (2) as the base case, the Italian apartment. The scenarios based on amount of wood furnishings were as follow: (1): low-intensity, (2) medium-intensity, and (3) high-intensity. Scenario 1 simulates the replacement of a (wood) parquet flooring system with a non-wooden flooring system to reduce overall wood volume whereas scenario 3 increased overall wood volume by adding both solid wood windows and parquet flooring systems to other areas of the apartment, the kitchen and bathroom not installed in scenario 2.

According to the calculation method provided by EN 16449:2014, the amount of CO₂-equivalents (CO₂-e) stored by each WBP is determined by Equation 1. CO₂-e or carbon dioxide equivalent, is a standard unit for measuring carbon footprints:

$$WBP_{CO_2} = 3,67 \times 0,5 \frac{\rho_w V F_w}{1 + \frac{\omega}{100}} \quad (1)$$

where WBP_{CO_2} is the amount, in kg, of CO₂-e stored by a WBP 3,67 is the ratio between the molecular weight of CO₂ and the atomic weight of C 0,5 is the fraction in weight of C in wood as given by EN 16449:2014, ρ is the density of wood in kg/m³ at moisture content on dry basis (MC_{db}) w , V is the volume, in m³, occupied by the WBP, F_w is the fraction of wood in V , ω is the MC, in percentage, of wood in the product. All calculation provided used MC on a dry basis. MC does not impact the carbon content of the wood structure itself but size does fluctuate as MC changes.

The variables included in Equation 1 (ρ , V , F_w , ω) were determined for each WBP included in the apartment, then the relative amount of CO₂ stored was calculated. The determination methods differed

depending on the type of WBP and are described as the following.

Solid wood

Since it was not possible to remove physical samples from the furnishings without damaging them, wood species for the furnishings were firstly macroscopically identified and then the density (r) of the wood was set according to the average reference values at 12% of MC given by Giordano (1997), the density values were adjusted according to Simpson (1993), depending on the MC of wood in the furnishings.

The MC (ω) of solid wood was determined through a contact hygrometer with accuracy $\pm 0,1\%$. When direct measurement of MC was not possible, reference values given for WBPs in residential and indoor environments were used (Bergman 2010, EWPA 2008).

The volume (V) of solid wood in furnishings was calculated by summing the volumes of all the components made of solid wood embedded in it, according to Equation 2:

$$V_{sw} = l_1 w_1 t_1 + l_2 w_2 t_2 + \dots + l_n w_n t_n \quad (2)$$

where V_{sw} is the volume, in mm^3 , of solid wood embedded in an artifact, and l , w and t are respectively the length, width and thickness, in mm, of the solid wood components 1,2...n embedded in the artifact.

Length, width, and thickness of all WBPs were determined in mm through a measuring tape in Class II of the European Weights and Measure Regulation.

Plywood

The density of wood embedded in plywood depends on the wood species and on the densification determined by the pressing phase in plywood production. To the purpose of this study the densification was considered of 4% according to Wang *et al.* (2006) and Wellons *et al.* (1983), and the density of wood constituting plywood was therefore calculated by Equation 3:

$$\rho_{wp} = \rho_r \times 1,04 \quad (3)$$

where ρ_{wp} is the density of wood included in plywood, ρ_r is the density of the wood species given by references 1,04 is the coefficient taking into account the densification of wood in plywood.

The volume (V) of plywood in furnishings were calculated as already reported in Equation 2 for solid wood.

As for the percentage of wood (F_w) in plywood, it is to consider that part of its volume was composed of resins (i.e. glue). To calculate the overall volume of the glue, the glue line thickness (which varies depending on pressure, glue etc.) was set to 0,1 mm according to Kurt and Cil (2012) and Baldwin (1995); the number of the glue lines was directly calculated since it was always possible seeing the cross section of plywood. The percentage of wood in plywood was then calculated, referring to its cross section, according to Equation 4:

$$F_{wp} = \frac{t_p - (t_{gl} n_{gl})}{t_p} \times 100 \quad (4)$$

where F_{wp} is the percentage of wood in the cross section of the WBP, T_p is the thickness of plywood, T_{gl} is the thickness of each glue line, n_{gl} is the number of glue lines.

The MC (ω) of wood in plywood was measured as already reported for solid wood.

Particleboard and MDF

Particleboard and MDF are made of wood and resin and produced with different densities and with final MC of about 10%, similar to that commonly found in indoor housing (Bergman 2010, EWPA 2008).

To the purpose of this study, it was considered, according to Wilson 2010a, Wilson 2010b that 1 m³ of particleboard and MDF have an oven-dried density of 671 and 666 kg/m³, respectively. The above values already take into account the fraction of wood lost as waste during manufacturing. Overall, for particleboard the Equation 1 can be rewritten as follows (Equation 5):

$$Pa_{CO_2} = 3,67 \times 0,5(671V_p) \quad (5)$$

where Pa_{CO_2} is the amount, in kg, of CO₂-e stored by particleboard 3,67 and 0,5 are the coefficient already defined in Equation 1, 746 is the content, in kg, of wood in 1 m³ of particleboard and V_p is the volume of the panel considered.

Similarly, for MDF the Equation 1 can be rewritten as follows (Equation 6):

$$MDF_{CO_2} = 3,67 \times 0,5(666V_p) \quad (6)$$

where MDF_{CO_2} is the amount, in kg, of CO₂-e stored by MDF 3,67 and 0,5 are the coefficient already defined in Equation 1, 741 is the content, in kg, of wood in 1 m³ of MDF and V_p is the volume of the panel considered.

All of the above methods were used for calculating the C stored by WBPs included in the apartment (scenario 2). For solid wood windows added to scenario 3, the dimensions, the density and the MC were set using the values given by data sheets of products commonly available on the market.

RESULTS AND DISCUSSION

First, each atom of C in wood subtracts from the atmosphere its entire molecule of CO₂ of origin. Therefore, because the molecular weight of CO₂ is substantially higher than the atomic weight of C, wood stores higher amount of CO₂-e than its own weight: for instance, through Equation 1 it can be calculated that 1 m³ of wood with density of 500 kg/m³ at 12% of MC stores 818 kg of CO₂-e, which is about 1,8 times its own oven-dried weight.

As for the results of the study, Figure 2 shows part of the living room to exemplify the measurements and calculations performed in the entire apartment.

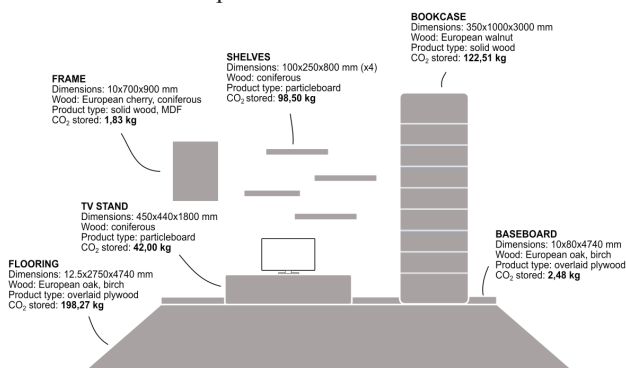


Figure 2: Part of the living room with all furnishings embedding WBPs colored in grey. Dimensions, wood species, WBP typology and kg of CO₂ stored are indicated for each of them.

Overall, the considered WBPs store 3531 kg of carbon dioxide. This amount is exclusively related to WBPs, whereas more carbon was stored or sequestered in the apartment by other objects, such as upholstery materials or houseplants, was outside the analysis of the present study. Carbon studies often compare the carbon stored with CO₂ emitted from cars; in this sense, the storage in the apartment corresponds to the CO₂ emitted by about 3 cars driving 10000 km in a year and emitting 120 g of CO₂ per km (European Environment Agency 2016).

The carbon stored in the apartment has some uncertainty because the densities of wood was taken from reference values that generally are listed with broad ranges to account for the variability of wood. These variances were investigated and did not result in large changes in the total amount of carbon stored. For example, the table in the kitchen was made of 0,042 m³ of sweet chestnut. Given a literature density of 572 kg/m³ at 8,8 MC, the carbon stored in it amounts to 40,62 kg CO₂-e. Considering the variability of wood, the density of sweet chestnut was altered by ±50 kg/m³ at the same MC (respectively, 522 kg/m³ and 622 kg/m³). The carbon stored varied from 37,07 kg to 44,17 kg (±8,7 %). Applying this approach to each WBP indicated the overall value of 3531 kg of carbon stored in the apartment varied from 3224 kg to 3838 kg.

Regarding the other variables in Equation 1, variations in MC had no impact in this case study, since in indoor housing the equilibrium MC (EMC) mainly ranges from 6 % to 10 % (Bergmann 2010). Furthermore, although the water contained within the WBP could increase and decrease base on surrounding EMC, the mass of carbon within the WBP does not change. As for the volume of WBPs, variations due to uncertainty of measurement are negligible in the context of the present study.

As for the contribution per WBP, almost half (46,6 %) of the carbon was stored by particleboard, followed by plywood and solid wood 24,9 % and 21,6 %, respectively whereas MDF accounts for just the 6,9 %. These fractions, however, strictly depend on the composition of the various furnishings and could have been very different. For instance, replacing the 12,5 mm thick plywood parquet flooring with a 12 mm thick laminate flooring would slightly change the overall amount of carbon stored (from 801 kg to 760 kg CO₂e) in the apartment, whereas the fractions per flooring product would be substantially different.

Storage fractions per furnishing provide a more stable indication, because in this case their overall volume, which has a remarkable relevance in Equation 1, is fixed. Grouping the furnishings in categories (Figure 3) shows that the closets store the 35,9 % (1266 kg), and the wardrobe alone the 17,7 % (624 kg); the parquet and baseboard store the 23,4 % (826 kg), the kitchen furniture the 11,7 % (414 kg), the inner and entry doors the 6,9 % (244 kg), the bookcases the 4,0 % (142 kg), the beds and couch a similar fraction (respectively 3,7 %, i.e. 131 kg, and 3,6 %, i.e. 128 kg). Other furnishings store more limited amounts.

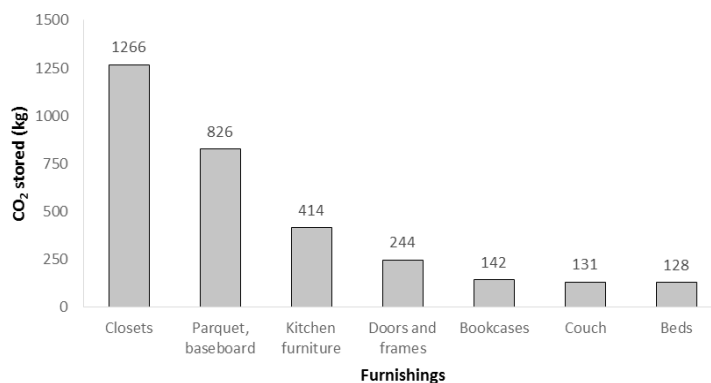


Figure 3: Main categories of wood based furnishings, in terms of kg of CO₂ stored, included in the apartment.

For those wooden species having higher commercial value (European oak, sweet chestnut, European walnut and cherry), they store the 17,8 % (628 kg) of the overall amount; in particular, the main fraction is represented by European oak of the parquet flooring (7,6 %, i.e. 268 kg). This limited amount reflects the fact that, in furnishing, the more expensive woods usually occupy minor volumes compared to cheaper woods.

As for scenarios 1, 2 and 3, removing the parquet flooring (scenario 1) determined a reduction of 23,4 %, whereas adding solid wood windows made of spruce, and parquet flooring (the same laid in the other rooms) in the bathroom and in the kitchen (scenario 3) increased the amount of 20,7 %. Overall, considering the indoor walkable area, the storage ranged from 35,1 kg/m² (2705 kg) of scenario 1, to 45,8 kg/m² (3531 kg) of scenario 2 and up to 55,3 kg/m² (4260 kg) of scenario 3. It is also to note that wooden windows added in scenario 3 would store 354 kg, representing the fourth main furnishing in terms of storage behind kitchen furniture (see Figure 3).

CONCLUSIONS

Reducing the concentration of atmospheric carbon dioxide is a fundamental challenge for the twenty-first century. Developing and identifying GHG mitigation strategies are vital to mitigating the impacts from climate change from increasing CO₂ level. One approach is quantifying the potential of carbon stored in wood products such as furnishings. Through the analysis of a case study, the present work investigated the carbon storage of furnishing WBPs. For the chosen apartment, the total amount of carbon stored by WBPs resulted in 3531 kg CO₂e, which correspond to 45,8 kg CO₂e/m² of indoor walkable area. Lower and higher usage scenarios, simulated by removing or adding WBPs, resulted in storages of 35,1 kg and 55,3 kg CO₂e/m² respectively. Carbon stored can be even higher, to mention some example, in apartments embedding exterior wooden claddings, as often happens in mountain areas, or structural WBPs. The potential substantial level of this carbon pool along wood structural elements ought to be considered when developing strategies on mitigating climate change.

Matching the above data with the number of apartments included in a metropolitan city illustrates the considerable relevance of furnishing WBPs in terms of carbon storage. Anyway, broad estimates should be taken with caution since many variables involved shall be carefully assessed, such as mean squared meters per apartment or furnishing types. Therefore, other studies are worthy of further investigation, for instance regarding housing types, furnishing styles and structural wood-based products.

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