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ASSESSMENT OF THE FURNITURE BOARD ECOLOGICAL FOOTPRINT: CASE STUDY OF A WOODWORKING ENTERPRISE IN THE CARPATHIAN REGION OF UKRAINE

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Abstract: *Understanding a product's ecological footprint has become incredibly important, as its assessment supports efforts to promote sustainable practices. However, there is limited knowledge about the specific environmental impacts of woodworking enterprises and their products. The purpose of the study is to evaluate the ecological footprint of a typical product from a woodworking enterprise in the Carpathian Economic Region of Ukraine. A middle-sized wood-processing enterprise was used as a case study. To achieve this objective, the study quantified the land area directly involved in producing 1 m^3 of furniture board. Also, the concept of a "virtual area" of land, essential for CO_2 absorption resulting from the transportation of raw materials for the production of 1 m^3 of furniture board, was applied. Then the methodological approach to determine the "virtual area" of land necessary for the absorption of CO_2 generated during the production of electricity which is spent on the operation of the main technological equipment and electricity consumption to produce 1 m^3 of furniture panel is considered. The overall ecological footprint of producing 1 m^3 of furniture board at the studied woodworking company is estimated as equivalent to 0.492 ha of forested area, from which only 3% of area is represented by direct land use - area used to produce wood for furniture board production.*

Key words: *ecological footprint, wood chain, forest sector, woodworking enterprise, Ukrainian Carpathians.*

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1. Introduction

As an expression of the understanding challenges of entering the era of global ecological overshoot environmental footprint indicators family developed in the middle of the 1990s to address local to planetary sustainability challenges. The Ecological Footprint measures the ecological assets that a given population or product requires to produce the natural resources it consumes (including timber and other forest products, space) and to absorb its waste, especially carbon emissions. It means that it tracks the use of productive surface areas such as forest area and the carbon demand on land. The number of publications on environmental footprint indicators has been growing rapidly, but with limited efforts to integrate different footprints into a coherent framework. Such integration is important for comprehensive understanding of environmental issues, policy formulation, and assessment of trade-offs between different environmental concerns [37]. The concept of ecological footprint was proposed in 1996 by economist William Rees and ecologist Mathis Wackernagel [39]. The ecological footprint is a systemic environmental accounting tool that is still one of the most widely used methodologies for sustainability assessments to this day [3, 7, 9, 10, 15, 16, 18, 19, 29, 36]. While economic valuation has so far been the most used approach – expressing the value of ecosystem services in monetary units – recent efforts have focused on alternative qualitative or biophysical accounting approaches to express the value of ecosystem services in physical units [25]. The goal of the ecological footprint is to determine the required amount of biologically productive land and marine area (ecological assets) that humanity directly or indirectly uses on a continuous basis to provide a specific set of essential services related to provisioning and regulation, considering prevailing resource management technologies and practices [25, 39].

The ecological footprint is an indicator based on area and considers the assets of the ecosystem where photosynthetic activity occurs and solar energy is captured by an autotrophic organism to harvest matter into all types of biomasses that are suitable for humans [25, 26, 34, 35]. Its area is measured in global hectares or hectares with the world average bio productivity [17, 34]. In turn, these areas belong to six different ecological assets or land types: cropland, forests, pasture, fishing grounds, built-up land, and land for carbon sequestration [17]. All these types of land areas are scaled according to their ecological productivity using corresponding scaling coefficients, namely equivalence and yield coefficients. A detailed and comprehensive description of the ecological footprint methodology can be found in Borucke et al. [5]. The ecological footprint has a wide range of applications and is a useful indicator for comparing systems of any scale (from small cities to nations) and monitoring by systems over time [26, 35, 39]. In conclusion, it can be stated that the ecological footprint represents a comprehensive measure of the impact of human activity on the surrounding environment, encompassing resource utilization and emissions, and facilitating the comparative analysis of this impact across various products or processes.

Similarly, like other indicators based on the ecological footprint (e.g., water footprint, land footprint, etc.), the rationale behind the ecological footprint is quite straightforward and intuitive: a higher ecological footprint value (i.e., the number of global hectares) indicates a greater environmental impact in terms of resource usage. Understanding a product's ecological footprint has become incredibly important as it encourages efforts to promote sustainable practices, develop cleaner technologies, and implement environmental policies and regulations to reduce pollution, manage resources sustainably, and facilitate the transition to renewable energy.

The Carpathian region of Ukraine represents a unique region abundant in natural resources, particularly forests, which are vital for biodiversity and ecosystem resilience. However, intensive development of the forest sector may lead to significant adverse effects on the environment, such as deforestation, water pollution, carbon emissions, and others.

Until now, any studies on determining the ecological footprints of wood based products have not been conducted in the Carpathian region of Ukraine. This underscores the importance and relevance of conducting such research in this region, especially considering the significant impact of economic activities on natural resources and ecosystems in the Carpathians. Conducting an analysis of the ecological footprints of the furniture industry can help balance production and nature conservation, which is critically important for ensuring sustainable development in the region.

Considering these preconditions, the primary objective of this study is to assess and analyze the ecological footprint associated with furniture board production, a representative wood-based product in the Carpathian region of Ukraine. This analysis will encompass the entire wood chain, from forest extraction to woodworking enterprises, with the overarching goal of formulating strategies for improved natural resource management, fostering the adoption of more efficient technologies, and implementing policies aimed at mitigating adverse environmental impacts. Furthermore, the utilization of the ecological footprint methodology will serve to promote the development of a mindful and responsible consumer behaviour and provide support to producers committed to upholding environmental responsibility.

2. Materials and Methods

2.1 Characteristics of Wood Products from the Selected Typical Woodworking Enterprise

The case study woodworking company is situated in the Lviv oblast of the Carpathian Economic Region of Ukraine. The enterprise was established in 1995. The company has been involved in various woodworking activities, including furniture production, wooden joinery, flooring, fuel briquettes and more. However, since 2005 the primary focus of the company has become the production of furniture board (Figure 1). The company exports all its products to EU countries such as Germany, Finland, Spain, Denmark, France, and others.

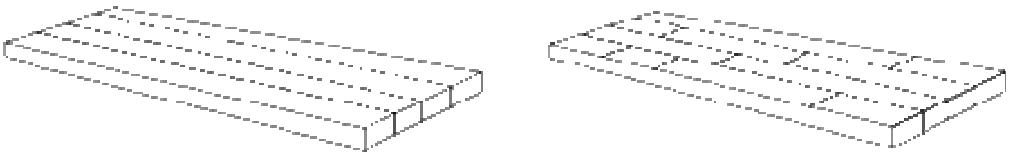

Fig. 1. *Construction of furniture boards made from solid slats and furniture boards made from slats that are joined lengthwise*

The current installed capacity of the enterprise allows to produce over 200 m^3 of furniture board per month, with lengths ranging from 700 to 5,000 mm, widths of 100-1,200 mm and thicknesses of 30-45 mm. The total number of production staff is 130 employees.

2.2 Methodology for Calculating the Ecological Footprint of a Product

The Ecological Footprint of a Product (EFP) determines the necessary resource demand on the environment caused by a product, service or activity. The proposed unit for EPF is the global hectare-year [21]. EPF is calculated as the sum of the footprints of all n-actions required for the creation, utilization, and disposal of product P, following the Life Cycle Assessment (LCA) approach [21, 28]. In general, the calculation formula will take the following form (Eq. (1)):

$$EFP = \sum_{i=1}^{n} \sum_{j=1}^{6} EFP_{i,j} \quad (1)$$

where: i is the number of inventoried objects participating in production chain P, and j - six different types of land being considered: cropland, forests, pasture, fishing grounds, built-up land, and land for carbon sequestration.

The calculation of the ecological footprint of each individual input element is performed using Equation (2):

$$EFP_i = \sum_{j=1}^{6} A_j \cdot YF_j \cdot EQF_j \quad (2)$$

The sum of *j* distinct land types is possible after transforming hectares (*A*) into global hectares (i.e., hectares with a world-average productivity) using the equivalence coefficient (*EQF*) and the yield coefficient (*YF*) [21, 39] – these are coefficients of scaling based on land productivity. The *EQF* coefficient converts a specific type of land (i.e., cropland) into a universal unit of biologically productive area, namely the global hectare, while the *YF* coefficient captures the difference between the national and global productivity indicators for this type of land [17]. The meaning of the coefficients is based on the agricultural suitability indices from the Global Agro-Ecological Zones (GAEZ) model [12]. After transformation, global hectares become hectares with the world-average productivity of all the considered land types, thus becoming global hectares. The *YF* and *EQF* coefficients for all types of land and countries for a specific year are calculated and provided by the Global Footprint Network (GFN) on an annual basis [20].

Additionally, special conversion coefficients are required for data that is not directly expressed in terms of area:

a) If the input data is expressed in units of mass (*M*, tons/year), they can be converted into units of area (*A*) using the transformation coefficient of relative land use efficiency (*Y*) specific to the product, region, and season (Equation (3) - [4, 17]:

$$A_i = \frac{M_i}{Y_i} \quad (3)$$

b) If expenses are expressed in terms of carbon dioxide equivalents, they can be converted into global hectares using the Equation (4):

$$A_{i\,Forest} = \frac{CDE_i}{AFCS} \quad (4)$$

where:

CDE_i is the equivalent value of carbon dioxide emissions specific to each type of pollutant i [tons of CO_2];

AFCS – Average Forest Carbon Sequestration is the long-term capacity of one hectare of world average forest ecosystem [tons Co_2/ha*year], to sequester atmospheric carbon dioxide through the photosynthesis mechanism. It has been recently updated to 0.73 or 2.67 tons Co_2/ha*year [25].

As a result of human activity, many harmful substances are formed, among which there are greenhouse gases. Greenhouse gases, in addition to carbon dioxide (CO_2), include: water vapour (H_2O), nitrogen oxide (N_2O), methane (CH_4), ozone (O_3), sulfur hexafluoride (SF_6), hydrofluorocarbon compounds, and perfluorocarbon compounds. For comparison and unification to one value, greenhouse gas emissions are converted into the carbon dioxide equivalent. For this purpose the Equation (5) was applied:

$$CDE_i = M_x \cdot E_{CO_2,\,T} \quad (5)$$

where:

M_x is the greenhouse gas emissions [tons];

E_{CO2} – the global warming potential of the greenhouse gas.

In general, the overall ecological footprint of a product can be divided into two components, referred to as direct (DIR) and indirect (IND), according to Equation (6):

$$EFP = EFP_{DIR} + EFP_{IND} \quad (6)$$

where:

EFP_{DIR} represents a product-specific ecological footprint associated with the direct land use of forests, cropland, pastures, and built-up land types required for the functioning of the production system;

EFP_{IND} – referred to as the "indirect" or "virtual land" needed to absorb CO_2 emissions [tons Co_2/ha*year], generated during production.

The ecological footprint of furniture boards production associated with direct land use was determined based on the rate of consumption of round timber to produce 1 m^3 of some furniture boards (3.81 $m^3/^{m3}$ – data from the enterprise) and the average timber stocks in the forests of Ukraine [14].

The virtual component of the ecological footprint of furniture board production is associated with processes such as:

a) Supply of raw materials to the enterprise because of the combustion of diesel fuel by internal combustion engines in automotive transport;

b) The production of electricity consumed for the operation of the main technological equipment and the lighting of production premises;
c) Production of heat for drying rough-sawn stock by burning production waste.

The raw material in the form of round timber is delivered to the enterprise by means of road transport. As a result of burning diesel fuel by internal combustion engines, carbon dioxide, nitrogen oxide, and methane are released, which are greenhouse gases. When calculating the “virtual land area” required for absorbing CO_2 as a result of raw material transportation, the following data was taken into account: the average transportation distance to the enterprise is 200 km (data from the enterprise), the cargo capacity of the transportation vehicles is 22 tons [30], the average fuel consumption per 100 km is 23 liters (from the technical characteristics of the company's trucks), and the density of freshly harvested oak timber – 990 kg/m^3 [38].

When determining the “virtual land area” required to absorb the CO_2 generated during the production of electricity that powers the technological equipment and lighting of production facilities for the furniture board production, the following data was taken into account: average monthly production productivity – 200 m^3 of furniture board (data from the enterprise), average monthly electricity consumption – 180,000 kWh (data from the enterprise), and the structure of electricity production in Ukraine. The structure of electricity production as of the beginning of 2022 is provided in Table 1 [38].

CO_2 emissions during the production of 1 kWh of electricity depending on the generation method are provided in Table 2 [13].

Structure of Electricity Production in Ukraine Table 1

No.	The method of electricity generation	Percentage in the structure [%]
1	Nuclear power plant	55
2	Thermal power plant	29.3
3	Hydroelectric power station	6.7
4	Renewable energy (solar, wind, bio-stations)	8

Table 2

CO_2 emissions in the production of 1 kWh of electricity depending on the generation method

No.	The method of electricity generation	Emissions of greenhouse gases [g, CO_2 eq/kWh]
1	Renewable energy	20
2	Hydroelectric energy	33
3	Nuclear energy	35–60
4	Electricity generation by burning natural gas	400
5	Electricity generation by burning coal	1,000

When determining the "virtual land area" required to absorb CO_2 generated during the production of heat energy for drying lumber by burning wood waste for the furniture board production, the following data was taken into account: consumption of wood waste for drying wood (0.27 m^3 of wood waste for drying 1 m^3 of lumber or 688 kg of oak wood waste for 1 m^3 of furniture board production - data from the enterprise) and the amount of greenhouse gases emitted in the process of burning wood (CO_2 – 1,304 kg/kg, N_2O – 0.023×10^{-3} kg/kg, CH_4 – 2.38×10^{-3} kg/kg) [7, 27]. When calculating the impact of greenhouse gases on the value of the virtual land area, for each type of greenhouse gas, its global warming potential was taken into account (E_{CO2} for N_2O is 298 and E_{CO2} for CH_4 is 25) [11]. The calculation of the ecological footprint for furniture board production, which is related to direct land use is based on the following indicators (Table 3).

Table 3

Indicators for calculating the ecological footprint of furniture board production, which is related to direct land use

No.	Indicator	Equations and explanations	Result
1	The rate of consumption of round timber for the production 1 m^3 of furniture boards	$$H = \frac{V_{rt}}{V_{fb}} \quad [m^3/m^3]$$ where: V_{rt} is the estimated volume of round timber (V_{rt} = 100 m^3); V_{fb} – the volume of manufactured furniture boards (V_{fb} = 26.21 m^3).	3.81
2	The area of land of direct use, which is necessary for production 1 m^3 of a furniture boards	$$EPF_{DIR} = \frac{H}{A} \quad [ha]$$ where: H is the rate of consumption of round timber for production 1 m^3 of furniture boards (H = 3.81 m^3/m^3); A – the average timber stocks in the forests of Ukraine (A = 251 m^3/ha) [33].	0.015

The calculation of the ecological footprint for furniture board production, which is related to fuel use because of the transportation of raw materials is based on the following indicators (Table 4).

The calculation of the ecological footprint for furniture board production, which is related to electricity consumption in production, is based on the following indicators (Table 5).

Table 4

Formulas for calculating the ecological footprint of furniture boards production, associated with the burning of diesel fuel by internal combustion engines of automotive transport during the supply of raw materials

No.	Indicator	Equations and explanations	Result
1	Permissible volume of round timber for simultaneous transportation by three-axle automotive transport	$$V = \frac{M_{max}}{\rho} \quad [m^3]$$ where: M_{max} is the maximum weight with simultaneous transportation by three-axle automotive transport (M_{max} = 22,000 kg); ρ – the density of freshly harvested oak wood (ρ = 990 km/m^3).	22.22
2	The volume of diesel fuel consumption for the round timber transportation	$$V_{fuel\,l} = \frac{L}{100} \cdot C + \frac{L}{100} \cdot \left(C + k_c \cdot M_{max}\right) \quad [l]$$ where: L is the average transportation distance of round timber (L = 200 km); C – the consumption of diesel fuel by an empty truck per 100 km (C = 23 l); M_{max} – the maximum weight which simultaneous transportation by three-axle automotive transport (M_{max} = 22 tons); k_c – the coefficient accounting for additional fuel consumption per ton of cargo (k_c = 1.3).	149.2
3	Amount of fuel used	$$V_{fuel\,t} = V_{fuel\,l} \cdot 0.001 \cdot K \quad [t]$$ where: $V_{fuel\,l}$ is the volume of consumption of diesel fuel for the transportation of round timber ($V_{fuel\,l}$ = 149.2 l); K – the average fuel conversion factor from liters to kilograms (density), for diesel fuel k = 0.85.	0.127
4	Emissions of CO_2 caused by diesel fuel burning	$$M_{CO_2} = 0.001 \cdot V_{fuel\,t} \cdot Q \quad [t]$$ where: $V_{fuel\,t}$ is the amount of fuel actually used in tons ($V_{fuel\,t}$ = 0.127 t); Q – the average specific emissions of carbon dioxide, for diesel fuel Q = 3138 kg/t.	0.398

5	Emissions of N2O caused by diesel fuel burning	$M_{N_2O} = 0.001 \cdot V_{fuel\,t} \cdot Q$ [t] where: $V_{fuel\ t}$ is the amount of fuel actually used in tons ($V_{fuel\,t}$ = 0.127 t); Q – the average specific emissions of nitrogen oxide, for diesel fuel Q = 0.12 kg/t.	0.000015
6	Emissions of CH_4 caused by diesel fuel burning	$M_{CH_4} = 0.001 \cdot V_{fuel\,t} \cdot Q$ where: $V_{fuel\ t}$ is the amount of fuel actually used in tons ($V_{fuel\,t}$ = 0.127 t); Q – the average specific emissions of methane, for diesel fuel Q = 0.25 kg/t.	0.000032
7	Specific emissions of CO_2 during the transportation of round timber for the production of 1 m^3 of a furniture boards	$M_{CH_2/m3} = \frac{M_{CO_2}}{\frac{V}{H}}$ [t] where: M_{CO2} is the emissions of CO_2 when burning diesel fuel (M_{CO2} = 0.398 t); V – the permissible volume of round timber for simultaneous transportation by three-axle automotive transport (V = 22.22 m^3); H – the rate of consumption of round timber for the production of 1 m^3 of furniture boards (H = 3.81 m^3/m^3).	0.068
8	Specific emissions of N_2O during the transportation of round timber for the production of 1 m^3 of furniture boards	$M_{N_2O/m3} = \frac{M_{N_2O}}{\frac{V}{H}}$ [t] where: M_{N2O} is the emissions of N_2O when burning diesel fuel (M_{N2O} = 0.000015 t); V – the permissible volume of round timber for simultaneous transportation by three-axle automotive transport (V = 22.22 m^3); H – the rate of consumption of round timber for the production of 1 m^3 of furniture boards (H = 3.81 m^3/m^3).	0.0000026
9	Specific emissions of CH_4 during the transportation of round timber for the production of 1 m^3 of furniture boards	$M_{CH_4/m3} = \frac{M_{CH_4}}{\frac{V}{H}}$ [t] where: M_{CH4} is the emissions of CH_4 when burning diesel fuel (M_{N2O} = 0.000032 t);	0.0000054

		V – the permissible volume of round timber for simultaneous transportation by three-axle automotive transport ($V = 22.22\ m^3$); H – the rate of consumption of round timber for the production of 1 m^3 of furniture boards ($H = 3.81\ m^3/m^3$).	
10	Specific emissions of N_2O in terms of CO_2 equivalents during the transportation of round timber for the production of 1 m^3 of furniture boards	$CDE_{N_2O/m3} = M_{N_2O/m3} \cdot E_{CO_2}$ [t] where: M_{N2O/m^3} is the specific emissions of N_2O during the transportation of round timber for the production of 1 m^3 of furniture boards ($M_{N2O/m^3} = 0.0000026$); E_{CO2} – the global warming potential of greenhouse gas (E_{CO2} for N_2O is 298).	0.0008
11	Specific emissions of CH_4 in terms of CO_2 equivalents during the transportation of round timber for the production of 1 m^3 of furniture boards	$CDE_{CH_4/m3} = M_{CH_4/m3} \cdot E_{CO_2}$ [t] where: M_{CH2/m^3} is the specific emissions of CH_4 during the transportation of round timber for the production of 1 m^3 of furniture boards ($M_{CH2/m^3} = 0.0000054$); E_{CO2} – the global warming potential of greenhouse gas (E_{CO2} for CH is 25).	0.00013
12	"Virtual land area" required to absorb the CO_2 generated during the round timber transportation for the production of 1 m^3 of furniture boards	$A_{1\ Forest} = \frac{M_{CO_2/m3} + CDE_{N_2O/m3} + CDE_{CH_4/m3}}{AFCS}$ [ha] where: M_{CO2/m^3} is the specific emissions of CO_2 during the transportation of round timber for the production of 1 m^3 of furniture boards ($M_{CH2/m^3} = 0.068$); CDE_{N2O/m^3} – the specific emissions of N_2O in terms of CO_2 equivalents during the transportation of round timber for the production of 1 m^3 of furniture boards ($CDE_{N2O/m^3} = 0.0008$); CDE_{CH4/m^3} – the specific emissions of CH_4 in terms of CO_2 equivalents during the transportation of round timber for the production of 1 m^3 of furniture boards ($CDE_{CH4/m^3} = 0.000013$); AFCS – the Average Forest Carbon Sequestration, is the long-term capacity of one hectare of world-average forest ecosystem to sequester atmospheric carbon dioxide through the photosynthesis mechanism (AFCS = 2.67 tons CO_2/ha·year).	0.026

Table 5

Formulas for calculating the ecological footprint of furniture boards production, associated with the electricity production consumed for the operation of the main technological equipment and lighting on the production premises

No.	Indicator	Equations and explanations	Result
1	Electricity consumption for the production of 1 m^3 of furniture boards	$$P_{m3} = \frac{P_{month}}{V_{fb\,month}} \quad [kW \cdot h]$$ where: P_{month} is the average monthly electricity consumption to support the operation of the production equipment and lighting on the premises (P_{month} = 180,000 kW·h); $V_{fb\ month}$ – the average monthly amount of furniture boards production ($V_{fb\,month}$ = 200 m^3).	900
2	Average weighted emissions of CO_2 during generation of 1 kW·h in the unified energy system of Ukraine	$$M_{CO_2/kW \cdot h} = \sum_{i=1}^{n} M_{CO_2 i} \cdot S_i \quad [g]$$ where: M_{CO2} is the CO_2 emissions during the production of 1 kW·h of electricity depending on the i-th generation method (Table 2); S_i – the share of electricity generation in the i-th method in the unified energy system of Ukraine (Table 1).	239.311
3	CO_2 emissions during electricity generation for the production of 1 m^3 of furniture boards	$$M_{CO_2/m3} = 10^{-6} \cdot M_{CO_2/kW \cdot h} \cdot P_{m3} \quad [t]$$ where: P_{m3} is the electricity consumption for production of 1 m^3 of furniture boards (P_{m3} = 900 kW·h); $M_{CO2/kW \cdot h}$ – the average weighted emissions of CO_2 during generation of 1 kW·h in the unified energy system of Ukraine ($M_{CO2/kW \cdot h}$ = 235.311 g).	0.21538
4	"Virtual land area" required to absorb the CO_2 generated during the electricity production consumed for the operation of the main technological equipment and lighting on the production premises for the production of 1 m^3 of a furniture boards	$$A_{2\ Forest} = \frac{M_{CO_2/m3}}{AFCS} \quad [ha]$$ where: $M_{CO2/m3}$ is the specific emissions of CO_2 during the electricity production consumed for the operation of the main technological equipment and lighting on the production premises for the production of 1 m^3 of furniture boards ($M_{CO2/m3}$ = 0.21538); AFCS – the Average Forest Carbon Sequestration, is the long-term capacity of one hectare of world-average forest ecosystem to sequester atmospheric carbon dioxide through the photosynthesis mechanism (AFCS = 2.67 tons CO_2/ha·year).	0.081

The calculation of the ecological footprint for furniture board production, which is related to the heat generation for drying sawn timber by burning production waste, is based on the following indicators (Table 6).

Table 6

Formulas for calculating the ecological footprint of furniture board's production, associated with the heat generation for drying sawn timber by burning production waste

No.	Indicator	Equations and explanations	Result
1	Consumption of wood waste for drying sawn timber for the production of 1 m^3 of furniture board	$W_{waste} = V_w \cdot \rho_w \cdot N_{st}$ [kg] where: V_w is the necessary amount of wood waste for thermal energy generation for drying 1 m^3 of sawn timber (V_w = 0.27 m^3); ρ_w – the density of oak wood (ρ_w = 930 kg/m^3); N_{st} – the norm of consumption of sawn timber for the production of 1 m^3 of furniture boards (N_{st} = 2.74 m^3/m^3).	688
2	Specific emissions of CO_2 during the burning of wood for drying sawn timber for the production of 1 m^3 of furniture board	$M_{CO_2/m3} = W_{waste} \cdot M_{CO_2/kg} \cdot 10^{-3}$ [t] where: W_{waste} is the consumption of wood waste for drying sawn timber for the production of 1 m^3 of furniture boards (W_{waste} = 688 kg); $M_{CO2/kg}$ – the amount of CO_2 remissions when burning 1 kg of wood ($M_{CO2/kg}$ = 1.304 kg).	0.897
3	Specific emissions of N_2O during the burning of wood for drying sawn timber for the production of 1 m^3 of furniture board	$M_{N_2O/m3} = W_{waste} \cdot M_{N_2O/kg} \cdot 10^{-3}$ [t] where: W_{waste} is the consumption of wood waste for drying sawn timber for the production of 1 m^3 of furniture boards (W_{waste} = 688 kg); $M_{N2O/kg}$ – the amount of N_2O remissions when burning 1 kg of wood ($M_{N2O/kg}$ =0.023·10^{-3} kg).	0.000016
4	The specific emissions of CH_4 during the burning of wood for drying sawn timber for the production of 1 m^3 of furniture board	$M_{CH_4/m3} = W_{waste} \cdot M_{CH_4/kg} \cdot 10^{-3}$ [t] where: W_{waste} is the consumption of wood waste for drying sawn timber for the production of 1 m^3 of	0.001637

		furniture boards (W_{waste} = 688 kg); $M_{CH4/kg}$ – the amount of CH_4 remissions when burning 1 kg of wood ($M_{CH4/kg} = 2.38 \cdot 10^{-3}$ kg).	
5	Specific emissions of N_2O in terms of CO_2 equivalents during the burning of wood for drying sawn timber for the production of 1 m^3 of furniture board	$CDE_{N2O/m3} = M_{N2O/m3} \cdot E_{CO2}$ [t] where: $M_{N2O/m3}$ is the specific emissions of N_2O during the burning of wood for drying sawn timber for the production of 1 m^3 of furniture boards ($M_{N2O/m3}$ = 0.000016); E_{CO2} – the global warming potential of greenhouse gas (E_{CO2} for N_2O is 298).	0.00477
6	The specific emissions of CH_4 in terms of CO_2 equivalents during the burning of wood for drying sawn timber for production 1 m^3 of a furniture board	$CDE_{CH4/m3} = M_{CH4/m3} \cdot E_{CO2}$ [t] where: $M_{CH4/m3}$ is the specific emissions of CH_4 during the burning of wood for drying sawn timber for the production of 1 m^3 of furniture boards ($M_{CH4/m3}$ = 0.001637); E_{CO2} – the global warming potential of greenhouse gas (E_{CO2} for CH is 25).	0.041
7	The "virtual land area" required to absorb the CO_2 generated during the burning of wood waste for drying sawn timber for the production of 1 m^3 of furniture board	$A_{3\ Forest} = \frac{M_{CO2/m3} + CDE_{N2O/m3} + CDE_{CH4/m3}}{AFCS}$ [ha] where: $M_{CO2/m3}$ is the specific emissions of CO_2 during the burning of wood for drying sawn timber for the production of 1 m^3 of furniture boards ($M_{CO2/m3}$ = 0.897); $CDE_{N2O/m3}$ – the specific emissions of N_2O in terms of CO_2 equivalents during the burning of wood for drying sawn timber for the production of 1 m^3 of furniture boards ($CDE_{N2O/m3}$ = 0.00477); $CDE_{CH4/m3}$ – the specific emissions of CH_4 in terms of CO_2 equivalents during the burning of wood for drying sawn timber for the production of 1 m^3 of furniture boards ($CDE_{CH4/m3}$ =0.041); AFCS – the Average Forest Carbon Sequestration, is the long-term capacity of one hectare of world-average forest ecosystem to sequester atmospheric carbon dioxide through the photosynthesis mechanism (AFCS = 2.67 tons CO_2/ha·year).	0.353

The overall ecological footprint of producing 1 m^3 of furniture board at the case study woodworking company is equivalent to 0.492 ha of forested area needed to compensate for the negative environmental impact of production. The largest proportion is attributed to the 'virtual land area' needed to absorb the CO_2 emissions generated during the combustion of wood waste for drying sawn timber in the production of 1 m^3 of furniture board. The smallest proportion, a mere 0.015 hectares, represents the actual direct land use for forestry operations, including forest planting and timber harvesting.

3. Results

The summarised results of the calculation of ecological footprint which are based on the following indicators presented in the Table 7. The ecological footprint structure for producing 1 cubic meter of furniture boards is depicted in Figure 2.

Table 7

Formulas for calculating the ecological footprint of a furniture board's production

No.	Indicator	Equations and explanations	Result
1	The total "virtual land area" required to absorb the CO_2 generated in for the production of 1 m^3 of furniture board	$EFP_{IND} = \sum A_{i\ Forest}$ [ha] where: $A_{i\ Forest}$ is the "virtual land area" covered with forest vegetation, which is necessary to absorb CO2 generated at various stages of the furniture boards manufacturing process.	0.46
2	Ecological footprint of furniture board production	$EFP = EFP_{DIR} + EFP_{IND}$ [ha] where: EFP_{DIR} represents a product-specific ecological footprint associated with the direct land use of forests, cropland, pastures and built-up land types required for the functioning of the production system (EFP_{DIR} = 0.015 ha); EFP_{IND} – the "indirect" or "virtual land" needed to absorb CO_2 emissions generated during production (EFP_{IND} = 0.46 ha).	0.475

4. Discussion

There is no clear consensus on the best available methodological approach for assessing the various impacts of production and consumption on the state of the environment despite its widely recognized importance. After all, it is an essential task for different sectors and at different levels: global, regional, and local, as well as at company level, a certain type of activity or supply chain, individual product or consumer. Such calculations can provide answers to questions about the effects of macroeconomic or sectoral development [23].

The EU has committed to achieve climate neutrality by 2050. This requires a rapid reduction of greenhouse gas (GHG) emissions and ensuring that any remaining emissions are balanced through CO_2 removals. Forests play a crucial role in this plan: they are currently the main option for removing CO_2 from the atmosphere and additionally, wood use can store carbon durably and help reduce fossil emissions [23].

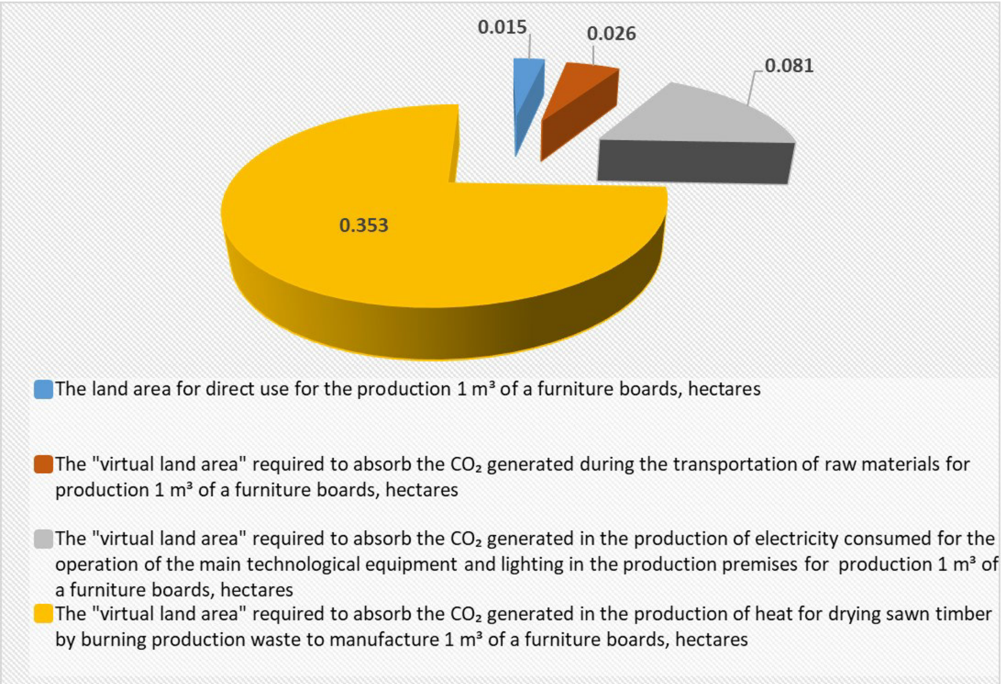

Fig. 2. *Structure of the ecological footprint for the process of 1 m^3 of furniture board production*

At the same time multiple environmental impacts occur throughout the wood supply chain from forest to sawmill and then to the final products (harvesting, transportation, and processing). For example, Aras and Kalaycıoğlu's study [2] estimated a comparative carbon footprint by calculation based on the LCA method for intermediate cutting (clear-cutting, selection thinning, increment thinning) and final harvesting in beech, oak, spruce, black locust, and hybrid poplar stands in Hungary [2]. Many studies have been conducted with the aim to identify environmental impacts of timber products. The studies have provided comprehensive coverage of different processes such as energy consumption, manufacturing process and their impacts on the environment [20]. The impacts can be minimized in various ways: changes in energy consumption behaviour, promotion of renewable energy, improved sawing and sawmilling practices, proper wood waste management, use of less toxic chemicals in the treatment of wood and timber products, and most importantly use of energy efficient and environment-friendly drying techniques and energy sources [1]. The role of forests in the EU climate policy has become more prominent. To stop and reverse the decline of the forest carbon sink, the EU has recently revised the regulation on land use, land-use change and forestry (LULUCF), and has set a target of − 310 Mt CO2e net removals for the LULUCF sector in 2030 [25].

A recent study examines data from the EU-23 from 2010 to 2020 using panel regression methods and explores the long-term relationships between ecological footprint types and circular economy indicators, such as per capita municipal waste generation, the municipal waste recycling rate, investment, circularity rate, and trade in recyclable materials [6]. Chen and Pao's study [6] revealed that ecological footprints showed negative or minimal growth, except for forest footprints. It has led authors to the conclusion that the EU should also diversify investments beyond energy efficiency, including protecting, restoring, and enhancing forests.

Considering the increasing application of ecological footprint data (as well as biodiversity footprint, carbon footprint, and other similar indicators) as a basis for informed decision [31] towards sustainable solutions, formulation of strategies aimed at environmental impact mitigation within the forest sector in Ukraine. Knowledge of the carbon footprint of wood utilization processes and the carbon storage of cut wood strongly influences the consideration of raw wood products as low-emission raw materials [22]. This information helps more accurately identify the role of technologies in climate change, climate risks, and sustainability issues [32]. The study found that the assumption that the Ecological Footprint is a useful indicator for assessing specific wood-based products in relation to resource use and carrying capacity is reasonable. Further improvements in data quality, methodologies, and assumptions are required for assessing a broader range of products taking into account specific regional conditions. The results can be extended to other areas, products and in the future, at company level. Future research can also be focused on identifying sets of indicators which can be combined with the Ecological Footprint. Therefore, region-specific and sector-specific studies can cover gaps in knowledge on the variety and scale of such impacts, and correspondingly on sustainable solutions.

5. Conclusions

It was established that the main source of negative environmental impact of the woodworking company's activity is associated with the generation of thermal energy required for wood drying. As a result, carbon dioxide is produced and the necessary forest area capable of absorbing the generated CO_2 over the course of a year is 0.37 hectares.

Applying the ecological footprint assessments to for other typical products can help identify the primary sources of environmental impact from industrial activities such as furniture production, and take steps to mitigate this impact. Analyzing the ecological footprint of the wood processing and furniture industry may involve assessing the use of forest resources for raw materials, energy, water, and other resources, as well as emissions from production and transportation.

In the context of studying the ecological footprint of a specific product from an enterprise, it becomes crucial to identify sustainable solutions for resource and energy management. This includes effective waste management practices according to circular economy principles. By assessing the ecological footprint across the entire product life cycle, we can proactively mitigate any adverse environmental impact.

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