Greenhouse Gas Emission Reduction Through Wood-Based Furniture Substitution: Analysis of Displacement Factors

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Substituting the use of non-renewable materials with wood-based products in the furniture industry is expected to reduce greenhouse gas (GHG) emissions. This substitution effect can be quantified by estimating the displacement factor (DF) of wood products. However, the lack of a standardized DF calculation method limits a reliable estimation of DFs for wood substitution in the furniture industry. Herein, DF values were determined for wood substitution in office furniture in Korea using three DF calculation methods, single DF, replacement rate-based DF, and more/less wood-intensive DF. The results indicated that substituting non-wood furniture with wood-based furniture can help reduce GHG emissions, with the most positive DF values observed. The negative DF values generated using the replacement rate-based DF method highlighted the importance of weight calculation when considering wood products. However, the difference in DF calculation methods between studies and the lack of life cycle assessment (LCA) data in Korea must be addressed. In conclusion, these results emphasize the need for a standardized DF calculation method and LCA data to improve the accuracy and applicability of the DF of wood-based furniture products. The present results provide insights into the environmental benefits of replacing non-wood products with wood products in the furniture industry.

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INTRODUCTION

Forests are crucial in regulating greenhouse gas (GHG) emissions and preventing climate change. Sustainable forest management contributes significantly to the prevention of desertification and land degradation (Yamanoshita 2019). Forests regulate atmospheric carbon levels by absorbing terrestrial carbon (Pan *et al.* 2011). Sustainable forest management helps conserve this carbon repository, preventing the carbon stored in trees from being released as CO_2, whereas newly planted trees reabsorb atmospheric carbon, contributing to the carbon cycle (Sathre and O'Connor 2010). Utilizing wood is an effective strategy for reducing GHG emissions, which involves substituting the use of non-renewable materials and energy with wood products (Geng *et al.* 2019a; Howard *et al.* 2021; Hurmekoski *et al.* 2021, 2022). Studies have reported that replacing nonwood materials and energy with wood reduces GHG emissions (Gustavsson *et al.* 1995; Sathre and O'Connor 2010; Geng *et al.* 2017, 2019a). However, such substitution necessitates a comprehensive consideration of its various aspects, as it involves structural and technological changes within the industry, as well as economic and social transformations (Gustavsson *et al.* 2006). Another approach is to adjust forest management scenarios to control production and harvesting levels, thereby altering carbon storage and emissions, which has been discussed extensively (Schlamadinger and Marland 1996; Jandl *et al.* 2007; Canadell and Raupach 2008; Alig *et al.* 2010). Proper harvesting, management, and species selection in forests can enhance carbon sequestration capabilities, maximize the role of forests as carbon reservoirs, and significantly contribute to GHG reduction (Jandl *et al.* 2007); however, this approach is limited to countries rich in forest resources and encounters practical difficulties in industrial linkages. Economic and large-scale management challenges associated with GHG emission reduction and forest management can be dealt with through supportive forest policies (Alig *et al.* 2010; Canadell and Raupach 2008). Therefore, focusing on the GHG reduction benefits of substituting non-wood products or energy with wood products and energy appears to be a relatively more realistic approach.

Manufactured wood consumes relatively less energy and stores more carbon than compared with non-wood materials such as steel, concrete, and plastic (Tsunetsugu and Tonosaki 2010), implying that substituting energy-intensive materials with wood can reduce carbon emissions and enhance the carbon storage capacity of end-products. Therefore, using wood products instead of nonwood alternatives can produce a substitution effect, thereby reducing GHG emissions (Werner *et al.* 2010). Wood products physically store atmospheric GHGs as carbon (incorporated into the holocellulose and lignin), making them an efficient means of carbon sequestration compared with fossil fuel-based products. However, it is essential to quantify these effects numerically to confirm whether wood product substitution effectively reduces GHG emissions compared with the use of non-wood products. This substitution effect of wood can be quantified by estimating the displacement factor (DF) of wood products.

The DFs of wood substitution have been analyzed in various fields, particularly in the energy and construction sectors, where wood is used as a substitute for materials, such as steel and concrete, with higher carbon footprints than those of wood (Myllyviita *et al.* 2021). Studies in these fields have demonstrated the significant potential of wood products to reduce carbon emissions (Myllyviita *et al.* 2021). However, despite their potential in analyzing the achievable GHG emission reduction, the estimation of the DFs of wood products in the materials, furniture, and product sectors remains limited.

According to Myllyviita *et al.* (2021), there are no established rules for determining the DFs of wood substitution; the methodology for DF estimation is decided based on previous studies or the suggestions of individual researchers. This diversity of DF calculation methods complicates the comparison of results across studies. For example, DFs can be calculated in various units, such as per ton of wood product, per cubic meter of wood product, per cubic meter of roundwood, and per hectare of forest (Gustavsson *et al.* 2007; Sathre and O'Connor 2010; Myllyviita *et al.* 2021). In addition, DFs have different units even within the same energy sector. For example, Fortin *et al.* (2012), Smyth *et al.* (2014), and Knauf *et al.* (2016) calculated DFs in units of megagrams per cubic meter of carbon (C) equivalents, megagrams of C per megagram of C, and tons of C per ton of C (tC/tC), respectively. Consequently, the calculation of DFs varies in terms of the system boundaries, carbon flows, purposes of DF estimation, and units. Therefore, the methodologies used for calculating the DF of wood substitution vary and lack standardization, making its consistent and accurate evaluation challenging, thus complicating the assessment of wood substitution efficiency.

Therefore, this study aimed to address the gaps in the existing research by focusing on DFs for wood-based furniture products, a sector much less explored for DF estimation compared with the energy and construction sectors. Through reviewing and analyzing various studies on DF, in this study, an attempt was made to identify the previously reported cases for estimating the DF of wood products in the furniture industry and the proposed respective DF calculation methods. The available DF calculation methods can be classified into three categories: single DF estimation, replacement rate-based DF estimation, and more/less wood-intensive DF estimation. This study also evaluated the potential of wood substitution to reduce GHG emissions in the furniture industry by determining DFs for wood substitution in the office furniture sector in Korea using relevant data regarding the office furniture products used in Korea provided by the Public Procurement Service, Korea (Nara Market).

Determining DFs for wood substitution for each product unit will help facilitate the estimation of achievable reductions in GHG emissions in the Korean furniture industry while enhancing the accuracy and comparability of DF research in the furniture industry. The results of this study contribute to the development of effective climate change mitigation strategies by providing reference standards for evaluating DFs for wood substitution in various industries, particularly the furniture industry.

EXPERIMENTAL

Displacement Factor Overview

The most commonly used method for calculating DFs for wood substitution is the single-displacement factor estimation proposed by Sathre and O'Connor (2010). When measuring DFs, non-wood products must be replaced with functionally equivalent wood products, implying that non-wood and wood materials must be used to create replacement products, defined as those that function identically in both functional and technical aspects (Hurmekoski *et al.* 2021).

The method for defining functional equivalence can be the same as the life cycle assessment (LCA) method, based on which the replacement product is derived, ensuring that the products being compared are functionally equivalent (Hurmekoski *et al.* 2021). A recent study measuring the carbon balance of apartment buildings using various structural frame materials (Tettey *et al.* 2019a) designed buildings to meet specific construction standards and ensured that all buildings had the same residential services and operational energy despite using different materials. Similarly, Tettey *et al.* (2019b) designed buildings to meet the energy performance standards of building codes and construction standards to ensure functional equivalence between products.

Between the two functionally equivalent products, the GHG emissions from using non-wood material products were measured and compared with the GHG emissions from using wood material products with equivalent performance. Therefore, the basic method for calculating DFs for wood substitution is to divide the difference in GHG emissions by the amount of wood used. However, DFs can be modified based on the environmental context, product diversity, and usage. Three methods for calculating DFs at the product-unit level were introduced.

Single DF estimation

Single DF is calculated using the below-mentioned steps. First, the GHG emissions from generated using a non-wood material product are measured. Subsequently, the GHG emissions of a wood material product with a performance equivalent to that of a non-wood product are measured. The DF for wood substitution is calculated by dividing the difference in GHG emissions by the amount of wood used. The calculated DF serves as an objective indicator for analyzing the effectiveness of wood products in reducing atmospheric GHGs compared with that of non-wood products (Sathre and O'Connor 2010; Leskinen *et al.* 2018).

The formula for calculating DF for wood substitution is as follows,

$$DF = \frac{GHG_{non-wood} - GHG_{wood}}{WU_{wood} - WU_{non-wood}} \tag{1}$$

where $GHG_{non\text{-}wood}$ and GHG_{wood} represent the GHG emissions from the use of non-wood and wood-substituted products, respectively. These are expressed in mass units corresponding to the CO_2 equivalents of carbon (C). WU_{wood} and $WU_{non\text{-}wood}$ represent the amounts of wood-substituted and non-wood-based products, respectively, expressed in mass units of C contained in the wood (Sathre and O'Connor 2010; Leskinen *et al.* 2018). A positive DF value indicates that the use of wood-based products results in lower GHG emissions than when using non-wood-based products.

Replacement rate-based DF estimation

The DF calculated using Eq. (1) indicates the substitution impact of wood-based products. However, it does not consider the wood substitution according to the product composition and usage. Equation (1) calculates DF based on the overall GHG emissions and wood storage of the product, making it difficult to determine which part of the product is effective for wood substitution. To improve this, a replacement rate (*R*) was introduced.

The equation for calculating the replacement rate is as follows,

$$R = -\left(\frac{WM_n(kg) - NWM_n(kg)}{Total\ \ wood\ \ (kg)}\right) \tag{2}$$

where *WM* represents the weight of the wood material in functionally classified wood products, and *NWM* represents the weight of non-wood material in functionally classified non-wood products. Each function must be identical. Total wood weight represents the total amount of wood used in the wood products.

The equation for calculating DF after applying the replacement rate is as follows:

$$DF = \frac{GHG_{non-wood} \times R - GHG_{wood}}{WU_{wood} - WU_{non-wood} \times R} \tag{3}$$

The replacement rate is obtained by dividing the weight of the replaced product by the weight of the final wood product (Schulte *et al.* 2021, 2022; Hammar *et al.* 2022). The introduction of the replacement rate concept enables the quantification of GHG emissions based on product usage and construction structure.

More/less wood-intensive DF estimation

This method for calculating DFs for wood substitution has been used in studies analyzing DFs for GHG emission reductions on a nationwide scale in Canada (Smyth *et al.* 2017). In this study, the authors compared the construction materials of two functionally equivalent products to evaluate the GHG emissions per functional unit. The end-use categories are set for the primary harvested wood product (HWP), and weights based on national consumption statistics are applied to reflect the overall national usage. This method is used for measuring DFs for wood substitution on a national scale. A similar weighting method has been applied in other studies. For example, Geng *et al.* (2019b) collected furniture within a selected range to estimate the wood substitution effect in a particular sector and estimated reductions in GHG emissions by comparing two functionally equivalent furniture products. More wood-intensive and less wood-intensive usage scenarios were selected, and weights were applied based on various sectors in the Chinese furniture market to derive emission reductions for each product. Finally, the DF of wood materials in end-use products was estimated based on the proportion of wood in the products.

The equation for calculating DF for a specific sector is as follows,

$$D_x = \sum_{i=1}^{n} \Delta m_i \times e_i \tag{4}$$

where D_x is the reduction in the emissions of wood products (products using more wood) compared with that of non-wood products (products using less wood) for end-use product x, n is the total number of materials used for the end-use product x, Δm_i is the mass difference (kg) between the i^{th} material of the wood and non-wood products, e_i is the emission factor for the i^{th} material, calculated as the carbon footprint (kg CO_2 eq.), and $\Delta m_i \times e_i$ is the emission difference (kg CO_2 eq.) between the i^{th} material of the wood and non-wood products. The weighted reduction in the emissions can be calculated using Eq. 5 as follows:

$$DW_x = D_x \times W_x \tag{5}$$

where DW_x is the weighted reduction in emissions (kg CO_2 eq.), calculated by multiplying D_x by the weight W_x. The weight of the product x can be calculated using Eq. 6 as follows,

$$W_x = \frac{S_x}{MR / \sum_{x=1}^{3} MR_x} \tag{6}$$

where W_x is the weight of the product x calculated by dividing the national wood material consumption ratio, S_x, in the end-use products by the proportion of wood used in a sector, S_x is the national wood material consumption ratio (%) of end-use products (Smyth *et al.* 2017), and MR_x is the mass (kg) of wood material in the end-use wood products. The weighted increment in the amount of wood used in the end-use product x can be calculated using Eq. 7 as follows,

$$MW_x = \Delta M_x \times W_x \tag{7}$$

where MW_x is the weighted increment in the amount of wood used in the end-use product x, calculated by multiplying ΔM_x by the weight W_x, and ΔM_x is the mass difference of wood material (kg) between wood products (products using more wood) and non-wood products

(products using less wood). The equation for calculating DFs for more and less wood usage scenarios is as follows,

$$DF = \frac{\sum_{x=1}^{3} DW_x}{\sum_{x=1}^{3} MW_x} \quad (8)$$

where DF is calculated by dividing the weighted reduction in emissions for the wood material based on the increment in the wood mass of each product. The unit is converted from kg CO_2 eq./kg wood to tons of carbon (tC)/tC, assuming 50% carbon content for wood (Geng *et al*. 2019b).

Displacement Factors for Wood-Based Furniture Products

The literature review confirmed that the furniture sector has significant potential for reducing GHG emissions. Seven previous studies have calculated 22 DFs for wood substitution in the furniture sector (Fortin *et al.* 2012; Knauf *et al.* 2015; Hurmekoski *et al.* 2020; Matsumoto *et al.* 2016; Rüter *et al.* 2016; Geng *et al.* 2019a, 2019b).

Table 1. Review of Displacement Factors for Wood-based Furniture Products

Reference	Country	Specific Description	Displacement Factor	Unit
Fortin *et al.* (2012)	France	Office furniture	0.043	Mg/m^3 of C eq.
		Kitchen furniture	0.069	
		Home furniture	0.043	
		Charis	0.043	
		Beds	0.043	
Knauf *et al.* (2015)	Germany	Doors (interior, exterior) - only framing/construction *vs.* steel, aluminum, PVC	1.62	tC/tC
		Wooden furniture (solid wood) *vs.* glass, plastic, metal	1.62	
		Wooden furniture (panel based) *vs.* glass, plastics, metal	1.42	
		Wooden kitchen furniture *vs.* glass, plastics, metal	1.62	
Hurmekoski *et al.* (2020)	Finland	Furniture replacement	0.9	tC/tC
Matsumoto *et al.* (2016)	Japan	Sawnwood and plywood; substitution of wooden furniture for metal furniture	43.2	kg C/m^3
Rüter *et al.* (2016)	Europe	Office furniture 2010	0.73	kg CO_2 eq./kg HWP
		Office furniture 2030	0.58	
Geng *et al.* (2019a)	China	Furniture Sector	1.36	tC/tC
		Kitchen furniture	0.11	
		Bedroom furniture	0.26	
		Living room furniture	0.85	
		Dining room furniture	-0.05	
		Commercial furniture	-107.73	
		Office furniture	6.2	
		Others furniture	2.83	
Geng *et al.* (2019b)	China	Furniture Sector	1.46	tC/tC

These studies quantitatively evaluated the positive environmental impact of wood used in the furniture sector and provided a foundation for applying similar approaches to other industries. The DFs ranged from a minimum of −107.73 to a maximum of 82.59, with variations depending on scenarios and methodologies set by each study. In addition, there were differences in the units used to calculate the DFs contributed to these variations.

Fortin *et al.* (2012) identified DFs for wood substitution in five furniture items, calculated by dividing the weight of the furniture by the reduction in GHG emissions per cubic meter. It was assumed that wood replaced steel and concrete. Knauf *et al.* (2015) set the DFs for four furniture items, calculated a single DF for wood substitution using LCA data, and then calculated volume-weighted DFs considering the distribution of wood usage, which indicates that the DFs for wood substitution can be set based on a quantitative distribution. Hurmekoski *et al.* (2020) calculated the DF for a single piece of furniture using sawn timber and plywood from the Finnish Environment Agency. Matsumoto *et al.* (2016) calculated the DFs for replacing metal furniture with wooden furniture and measured the carbon weight per cubic meter using a wood utilization model. Rüter *et al.* (2016) estimated DFs for wood substitution in office furniture based on annual use scenarios and calculated the DFs per unit weight of HWP. Geng *et al.* (2019a) determined DFs for eight furniture sectors and compared and analyzed the DFs for each scenario. Geng *et al.* (2019b) calculated DFs for the same eight furniture sectors described in Geng *et al.* (2019a) and estimated GHG reductions by comparing products with different wood intensities. They particularly examined cases where it was challenging to generalize the benefits of replacing high-energy metals and boards with wooden materials.

The issues faced in calculating the DFs for wood substitution in the furniture industry are similar to those in other industries. The first is the diversity of methods used to calculate DFs in each study. Owing to the differences in the scenarios and situations set in each study, it is difficult to establish consistent criteria when comparing DF calculations, thereby hindering the accurate assessment of substitution efficiency. Therefore, the standardization of DF calculation units is required. The second issue is the lack of transparency in the DF calculation methods. Recent studies have tended to disclose DF calculation methods to a certain extent, but when they do not, it is difficult to verify the calculation methods and sources, thus failing to provide the necessary information for subsequent research. For example, Fortin *et al.* (2012) mentioned the source of the DF but did not disclose the specific calculation methods used, and Knauf *et al.* (2015) did not specify the DF calculation process or reference papers. This situation is linked to the issue of the non-standardized DF calculation methods, making it difficult to rationally infer DF values in each study. Thus, the application of the DF calculation methods in the furniture industry is challenging.

The literature review revealed that the furniture sector has significant potential for reducing GHG emissions. Several studies on DFs for wood substitution in the furniture sector have quantitatively evaluated the positive environmental impact of wood use, providing a foundation for applying similar methodologies in other industrial sectors.

Displacement Factors for Wood-based Furniture Products in Korea

Previous studies on the potential for GHG emission reduction through wood product substitution revealed that wood product substitution in the furniture sector could play an important role in reducing overall GHG emissions. Therefore, this study used the product specifications (PPS 2024) provided by the Public Procurement Service, Korea, to calculate the weight of each furniture product and estimate the CO_2 emissions to calculate the DFs for wood substitution in office furniture. The specific office furniture items are listed in Table 2.

Table 2. Korean Non(less) Wood-based Furniture Products Used in Korea

Furniture	Purpose	Materials	Size (mm)	Carbon Emissions (kg C eq.)
Chair* (JS-06)	Back plate	PB	360 × 180 × 10T	0.05
	Back plate frame	Steel	Ø22.0 × 1.4T × 400(and 360)	0.37
	Base plate	PB	400 × 360 × 10T	0.12
	Base plate frame	Steel	Ø22.0 × 1.4T	0.37
	Chair legs	Steel	Ø60 × 27 × 1.4T × 460	0.59
	Reinforcement stand	Steel	Ø22.0 × 1.4T × 360	0.11
	Chair leg rest	Steel	Ø47 × 36 × 1.4T × 400	0.49
Desk* (FS2-R1200)	Top plate	PB	1200 × 800 × 23T	1.87
	Legs	Steel	30 × 50 × 1.4T	2.15
	Reinforcement stand	Steel	20 × 40 × 1.4T	2.23
Cabinet* (KSF401)	Top plate	Steel plate	350 × 850 × 6	9.03
	Side plate		350 × 890 × 6	18.92
	Back plate		890 × 850 × 6	22.97
	Base plate		350 × 850 × 6	9.03
	Shelf		350 × 850 × 6	18.07
	Reinforcement stand		90 × 890 × 6	2.43

* The information and specifications of the product were obtained from the Public Procurement Service, Korea (PPS 2024)

The chairs and desks were primarily composed of particle board and steel, whereas the cabinets consisted of steel sheets. Carbon emissions were calculated based on the carbon footprint provided by the environmental performance evaluation coefficient of the Korea Environmental Industry and Technology Institute (KEITI) (KEITI 2024). The equation for calculating carbon emissions is as follows:

$$Carbon\ emission = Carbon\ \ footprint(kg\ CO_2eq.) \times mass(kg) \times {}^{12}\!/\!_{44} \qquad (9)$$

where 12/44 is the CO_2 conversion factor. The calculated carbon emissions ranged from 0.05 kg C eq. to a maximum of 22.97 kg C eq., with variations observed based on the material used.

Table 3 shows the analysis results calculated assuming that non-wood materials were replaced with wood. Non-wood and wood-based furniture products were assumed to be functionally equivalent, with specifications suitable for the function and strength of each material. Carbon emissions were calculated using the same methods as described in Table 2 and ranged from 0.05 kg C eq. to a maximum of 1.87 kg C eq. In addition, the carbon storage capacity of the wood was calculated by multiplying the wood weight based on the carbon content ratio (PB = 0.451, MDF = 0.427) (Hiraishi *et al.* 2014) (Eq. 10), ranging from 0.04 kg C eq. to a maximum of 5.94 kg C eq.

$$Carbon\ storage\ = \ Mass\ of\ \ wood(kg) \times Carbon\ content(kg\ C\ eq.) \qquad (10)$$

Table 3. Wood-based Furniture Products Used in Korea

Furniture	Purpose	Materials	Size (mm)	Carbon Emissions (kg C eq.)	Carbon Storage (kg C eq.)
Chair* (assumption)	Back plate	PB	360 × 180 × 10T	0.05	0.17
	Back plate frame	MDF	Ø22.0 × 400 (and 360)	0.06	0.13
	Base plate	PB	400 × 360 × 10T	0.12	0.39
	Base plate frame	MDF	Ø22.0 × 400 (and 360)	0.06	0.13
	Chair legs	MDF	Ø60 × 27 × 460	0.16	0.35
	Reinforcement stand	MDF	Ø22.0 × 360	0.02	0.04
	Chair leg rest	MDF	Ø47 × 36 × 400	0.14	0.31
Desk* (assumption)	Top plate	PB	1200 × 800 × 23T	1.87	5.94
	Legs	MDF	30 × 50 × 721	0.58	1.28
	Reinforcement stand	MDF	20 × 40	0.43	0.94
Cabinet* (assumption)	Top plate	Particle board	350 × 850 × 23	0.58	1.84
	Side plate		350 × 890 × 18	0.95	3.01
	Back plate		890 × 850 × 18	1.15	3.66
	Base plate		350 × 850 × 23	0.58	1.84
	Shelf		350 × 850 × 18	0.91	2.88
	Reinforcement stand		90 × 890 × 6	0.04	0.13

* The information and specifications of the product were obtained from the Public Procurement Service, Korea (PPS 2024)

Table 4. Mass of the Compared Products

Furniture	Materials	Less Wood-Intensive (kg)	More Wood-Intensive(kg)
Chair	Steel	2.21	0.00
	Particle board	1.24	1.24
	MDF	0.00	2.25
Desk	Steel	5.04	0.00
	Particle board	13.16	13.16
	MDF	0.00	5.20
Cabinet	Steel	126.07	0.00
	Particle board	0.00	29.63

Table 5. Differences in the Mass and Greenhouse Gas Emissions of All Materials

Furniture	Materials	e_i* (kg CO_2 eq.)	Δm_i (kg)	D_x (kg CO_2 eq.)
Chair	Steel	2.34	-2.21	-3.59
	PB	0.5216	0.00	
	MDF	0.7091	2.25	
Desk	Steel	2.34	-5.04	-8.09
	PB	0.5216	0.00	
	MDF	0.7091	5.20	
Cabinet	Steel	2.34	-126.07	-279.55
	PB	0.5216	29.63	

* Collected from the Korea Environmental Industry and Technology Institute (KEITI 2024)

To calculate the more/less wood-intensive DFs, Table 4 categorizes the masses of materials into non-wood and wood-based products into fewer scenarios than those used for calculating the other two DF types. Using the data from Table 4, the reduced emissions of wood-based products compared with those of non-wood products in the final-use products were calculated by multiplying the mass differences of materials by the emission factors provided by KEITI (KEITI 2024) (Table 5). The results showed emissions reductions of 3.59, 8.09, and 279.55 kg CO_2 eq. for the chairs, desks, and cabinets, respectively.

Table 6. Weighting Factors of Products

Furniture	ΔM_x (kg)	MR_x(kg)	S_x(%)	W_x	DW_x (kg CO_2 eq.)	MW_x(kg)
Chair	2.25	3.49	0.33	4.91	−17.63	11.04
Desk	5.20	18.36	0.33	0.93	−7.56	4.86
Cabinet	29.63	29.63	0.33	0.58	−161.92	17.16

The domestic wood material consumption ratio for the end-use products was assumed to be 1:1:1, with each product assumed to consume approximately 33% wood. Based on this assumption, the DFs were measured for substitution in the three furniture items, assuming that all products consumed wood material equally. When weights were applied, the emission reductions for chairs, desks, and cabinets were 17.63, 7.56, and 161.92 kg CO_2 eq., respectively, indicating that weighting significantly impacted emission reductions.

RESULTS AND DISCUSSION

Calculation of Each DF Category

Based on the specifications of furniture products, in this study, the methods of calculating DFs for wood substitution were examined based on the carbon storage and emissions and characteristics of furniture products. Three methods for calculating DFs were investigated: single DF estimation, replacement rate-based DF, and more/less wood-intensive DF. Each DF category was calculated in units of tC/tC.

Table 7. Displacement Factors (DFs) of Wood-Based Furniture Products Used in Korea

Furniture	Single DF Avg. (tC/tC)	Replacement-Based DF Avg. (tC/tC)	Furniture	More/Less Wood-Intensive DF (tC/tC)
Chair	1.27	-0.44	Korean office furniture	3.09
Desk	1.03	-0.45		
Cabinet	7.60	3.18		

Table 7 shows DFs for wood substitution in Korean furniture products. The following inferences can be drawn based on these results. First, a single DF estimation is the most basic method for calculating DF for wood substitution and involves a simple comparison of the carbon emission and carbon storage characteristics of the products. The DFs calculated using this method were 1.27, 1.03, and 7.60 tC/tC for chairs, desks, and cabinets, respectively, confirming a reduction in GHG emissions reduction in all cases. Cabinets exhibited the most significant DF value. Second, the replacement rated-based DF estimation method calculates DF by adding the replacement ratio (R) to the single DF estimate. In this method, DF is calculated by multiplying the carbon emissions and carbon storage of non-wood materials by the replacement ratio. The results showed a DF of 3.18 for the cabinets, indicating a displacement effect. However, the chairs and desks had DFs of −0.44 and −0.45, respectively, indicating no displacement effect. The negative values for the chairs and desks suggest that the weight difference between wood and non-wood materials negatively affects displacement. However, for cabinets, this difference positively affects displacement effect. Finally, the more/less wood-intensive DF estimation method determined the DF per functional unit of a product. In this study, office furniture, including chairs, desks, and cabinets were defined as functional units, and DF was calculated by comparing GHG emissions from wood-based and non-wood-based products. The total amount of avoided CO_2 emissions was 187.1 kg CO_2 eq., and the incremental amount of wood was 33.06 kg. Assuming that the carbon content of the wood was 50% (Geng *et al.* 2019b), the calculated DF was 5.66 kg CO_2 eq./kg or 3.09 tC/tC, indicating that wood substitution in Korean office furniture has a positive impact on reducing GHG emissions across various furniture types.

Comparative Analysis of DF Categories

The single DF estimation method showed positive effects on GHG emissions reduction for all three furniture categories, which indicates that the use of wood-based products significantly reduces GHG emissions compared with the use of non-wood products. A simple comparison of the material composition and weight differences of each furniture product makes single DF estimation a valuable method for a simple comparative analysis of the two product types.

The replacement rate-based DF estimation method resulted in lower overall DF values than those estimated by the single DF estimation method, with negative DF values for chairs and desks but not cabinets. This result indicates a positive substitution effect for heavy items such as cabinets. The replacement rate-based DF estimation method applies the weight ratios of wood and non-wood materials to DF estimation, significantly affecting the product weight. Products designed to withstand the same load use wood materials without empty spaces, whereas nonwood materials have hollow structures due to their design processes and structural characteristics. In addition, even for the same volume, density differences between materials result in weight differences. Consequently, even for functionally equivalent products designed to withstand the same load, weight differences result in negative DF values under weighted conditions. The characteristic of DF fluctuating significantly with weight indicates that a positive DF value could be achieved by appropriately setting the weights of the non-wood products. However, this requires additional criteria because functional equivalence must be guaranteed for substitution products.

The more/less wood-intensive DF estimation method showed overall positive DF values within the range for Korean office furniture. This method is used for evaluating GHG emissions based on functional units rather than the weights of specific materials, making it suitable for broad assessments across various furniture types.

The results of this study suggest that substituting wood with non-wood furniture with wood-based furniture can significantly reduce GHG emissions. Based on the perspective of GHG emissions, simple comparisons of products can be used to estimate

DFs using a single DF estimation, whereas the replacement rate-based DF estimation method is suitable for calculating DFs based on the material weight or composition. Additionally, the more/less wood-intensive DF estimation method can be used for comprehensive DF measurements of functional units.

Absence of LCA Data in Korea

Most studies on the impacts of DF estimation on reducing GHG emissions (Sathre and O'Connor 2010; Leskinen *et al.* 2018; Schulte *et al.* 2021, 2022; Hammar *et al.* 2022) predicate their environmental impact analyses on LCA (Leskinen *et al.* 2018). It is a tool developed to evaluate environmental impacts within various systems (Finnveden and Moberg 2005), assessing resources and environmental impacts throughout the entire life cycle of a product, from raw material acquisition to the production, use, and end-of-life stages (Finnveden *et al.* 2009). The analysis conducts an impact assessment based on a life cycle perspective (Finnveden *et al.* 2009). The LCA evaluations of wood product substitution can assess the environmental impacts in specific industries through various substitution management scenarios (Hossain and Poon 2018) and analyze the environmental impact indicators derived from each production process (Höglmeier *et al.* 2015).

However, owing to the lack of LCA data regarding wood materials and product manufacturing in Korea, in this study, it was not possible to use LCA data for environmental impact analysis, such as GHG emission calculations. Therefore, the carbon-emission factors used in this study and the calculated DF values were not closely guaranteed within the LCA data. According to Odey *et al.* (2021), most LCA research in Korea currently focuses on construction and energy, with relatively less emphasis on other sectors. Therefore, more detailed LCA data regarding wood and manufacturing sectors in Korea are needed to more accurately analyze the environmental impacts of wood substitution in various other sectors.

Requirements to Standardize DF Calculation Methods

Considerable differences exist in the DF calculation methods used across studies, with differences in system boundaries, carbon flows, DF usage, and units, necessitating standardization and alignment. The expected effects of DF standardization are presented below. First, standardization enhances the comparability of the research results. If the DFs derived from various studies are based on consistent criteria and methodologies, comparing the research results and DFs becomes relatively easy. Second, it increases the utility of policymaking processes. When formulating policies related to the environment, more apparent comparisons and evaluations can be made based on standardized DFs, allowing for more effective policy development.

However, a research consensus is evidently needed for such standardization. An agreement on the criteria and methodologies used to calculate DFs in research and industry is essential. This could enhance research utilization and contribute to bridging the gap between actual industry and research. This standardization must also be continuously agreed upon and updated to reflect new research results and advancements.

In summary, standardizing DFs for wood substitution can play a significant role in responding to climate change and ensuring sustainable resource use worldwide, enabling a more accurate evaluation of the actual environmental benefits of wood use, and will help in developing effective policies and strategies for sustainable development.

CONCLUSIONS

1. Consistent with the results of previous studies on displacement factor (DF) estimation, the use of wood products in Korean furniture generally showed positive substitution effects compared with the use of non-wood products. This substitution effect was evaluated using three DF calculation methods: single DF estimation, replacement rate-based DF, and more/less wood-intensive DF. Single DF estimation provides a simple comparison between products, replacement rate-based DF includes the weight differences of materials, and more/less wood-intensive DF evaluates the substitution effects of functional units.
2. Weight differences due to material composition were found to play a crucial role in the DF estimation results. Owing to differences in the density and structural characteristics of materials, weight differences occur even for the same volume, necessitating positive substitution effects within the limits of guaranteeing functional equivalence. Therefore, additional criteria are required to ensure functional equivalence within products.
3. The lack of previous life cycle assessment (LCA) studies in Korea makes it challenging to accurately evaluate the environmental impacts of wood substitution, including GHG emission calculations. Therefore, there are limitations to the accuracy of the environmental impact analysis, and more detailed LCA data are needed for use in the Korean industry. Standardized DF calculations and improved LCA data can help develop effective strategies and policies for reducing greenhouse gas (GHG) emissions through wood product substitution in the furniture industry.

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