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A new model for predicting carbon storage dynamics and emissions related to the waste management of wood products: introduction of the HWP-RIAL model

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SUMMARY

The ability of wood products to store carbon allows for their significant contribution to the climate mitigation efforts and the emission reduction commitments set by the EU. In order to optimise the carbon storage capacity of wood products, it is important to take climate mitigation aspects into consideration as much as possible during their production, use and waste management. The aim of this study was to quantify the effects of product development, recycling, and waste management technologies on carbon storage and emissions. In the frame of the ForestLab project, a new model and decision support tool was developed, which is able to predict the duration of carbon storage of wood products and the evolution of emissions from them. The developed HWP-RIAL model (Harvested Wood Product Recycling, Incineration And Landfill model) uses the methodology of the Intergovernmental Panel on Climate Change (IPCC) to calculate emissions, which is also used in the National Greenhouse Gas Inventory report. It combines the IPCC waste model with equations describing the carbon storage and emissions of wood products, and the model is also supplemented with a self-developed recycling and waste routing module. This paper provides insight into the operation of the model by following the life cycle of 200,000 m^3 particle board.

Keywords: *harvested wood products; climate mitigation; recycling; incineration, landfill, CO_2*

INTRODUCTION

The ForestLab project (Borovics, 2022) of the University of Sopron which started in 2022 is related to climate change mitigation and adaptation. The main objective of the project is to investigate how the joint role of forestry and the wood industry can be increased in mitigating the effects of climate change. The ability of wood products to store carbon allows for their significant contribution to the climate mitigation efforts and the emission reduction commitments set by the EU (IPCC, 2022; Verkerk et al., 2022; Borovics and Király, 2022a/b).

To optimise the carbon storage capacity of wood products, it is essential to take into consideration the climate mitigation aspects as much as possible during their production, use and waste management. Therefore, we need to quantify the effects of product development, recycling and individual waste management technologies on carbon storage and emissions. To achieve these goals, in the framework of the ForestLab project, a new model and decision support tool was developed, which is able to predict the duration of carbon storage of wood products and the evolution of emissions during their waste management. Although industrial wood waste and by-products, as well as wood packaging waste are recycled on a large scale in Hungary, the largest amount of waste collected by the public utility (which, according to the estimate used in the Greenhouse Gas Inventory, contains approx. 50% wood) goes to landfill.

The EU is moving towards a circular bioeconomy with strong emphasis on waste reduction, reuse, recycling, cascade systems, and resource efficiency (EC, 2014). Circular bioeconomy is a recent concept defined as the common part of bioeconomy and circular economy (Carus and Dammer, 2018). It consists of the use of biomass in a sustainable way and the valorization of biomass resources, by-products and biowastes efficiently within the production chain (Goncalves et al., 2021). It incentivises the utilisation of residues and post-consumption wastes, and circularity concepts, such as cascading, to optimise the lifespan of products (Stegmann et al., 2020). Under the EU's bioeconomy strategy, wood-based bioeconomy innovations are expected to produce a stream of marketable substitutive products, such as lignin-based products, textiles, polymers, chemicals, oils, and construction materials (Giurca and Befort, 2023). A comprehensive understanding of the whole forest-based sector and of forest biomass use is key to support circular bioeconomy and can be performed following a material flow analysis perspective, as well as forest and wood product models (Goncalves et al., 2021).

Wood product models and life cycle assessment (LCA) tools are used to estimate the carbon dynamics of harvested wood products (Brunet-Navarro et al., 2018). Wood product models use production and trade data of wood commodities from statistical databases (Rüter, 2011; Rüter, 2016; IPCC, 2014; IPCC, 2019; Aleinikovas et al., 2018; Börcsök et al., 2011; Király et al., 2022; Kohlmaier et al., 2007) or harvested wood estimates produced by forest-growth models (Profft et al., 2009; Fortin et al., 2012). The harvested wood product category is also part of the Greenhouse Gas Inventory reporting and IPCC guidance is provided in order to enhance uniform and accurate reporting (NIR, 2022; IPCC, 2006; IPCC, 2019). The first order decay model by the IPCC is the basis of several wood product models (Brunet-Navarro et al., 2016; Rüter, 2011;

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Rüter, 2016; Király et al., 2022). The increasing complexity of wood product models allows for the advanced analysis of industrial product conversion efficiency, product lifespan, and recycling rate (Brunet-Navarro et al., 2018). Recycling has been identified as an important factor affecting the amount of carbon stored in wood products (Budzinski et al., 2020; Essel et al., 2014; Klein et al., 2013; Sokka et al., 2015; Vis et al., 2016; Werner et al., 2010). To handle recycling in wood product models, a common methodology is to assign a recycling rate to each product category, and then allocate recycled products to the same product category, CO2FIX (Schelhaas et al., 2004), LANDCARB (Krankina et al., 2012), and CAPSIS (Fortin et al., 2012) models process this way. Other wood product models (Brunet-Navarro et al., 2018) use enhanced cascade chains by replacing infinite recycling loops with one or two recycling loops, and by changing the use and lifetime of recycled products.

Most wood product models exclude emissions from landfilling, since carbon stock in landfilled wood products is not accounted for in the land use, land-use change and forestry (LULUCF) sector of Greenhouse Gas Inventories according to the IPCC methodology (IPCC, 2014; IPCC, 2019). To estimate the magnitude of methane and carbon dioxide emissions from landfilled wood waste the IPCC waste model (IPCC, 2006; IPCC, 2019) is a suitable tool. LCA software applications can also be used to assess the greenhouse gas emissions of the wood industry (Pichancourt, 2018). However, most of the LCA tools show major limitations on the assessment of uncertainties associated with the data and assumptions related to the complex lifecycles under the LULUCF and the waste sector (Pichancourt, 2018). Gentil et al. (2010) reviewed 15 LCA tools related to the waste sector, and they found that uncertainty assessment was applied in only 4% of the case studies (Gentil et al., 2010; Laurent et al., 2014). In the case of the LULUCF carbon-accounting tools, similar observations were made (Whittaker et al., 2013; Brunet-Navarro et al., 2016) stating that most software and tools do not implement any features for uncertainty assessment.

The presented HWP-RIAL model (Harvested Wood Product Recycling, Incineration And Landfill model) is an IPCC-based model combining the IPCC wood product model (IPCC, 2019; Király et al., 2022) and the IPCC waste model (IPCC, 2006). Both models are used in the Hungarian Greenhouse Gas Inventory (NIR, 2022). The HWP-RIAL model is a substantially newly developed version of the two IPCC models as it is supplemented with a waste route selection and a recycling module. It is also a new feature that the model is able to estimate greenhouse gas emissions originating from end-of-life incineration and from landfills, as well as carbon storage dynamics, and the amount of carbon stored in the products and at solid waste disposal sites. This paper presents the functionality of the HWP-RIAL model.

MATERIALS AND METHODS

The developed HWP-RIAL model (Harvested Wood Product Recycling, Incineration And Landfill model) uses the methodology of the Intergovernmental Panel on Climate Change (IPCC) to calculate emissions, the same methodology is also used in the preparation of the National Greenhouse Gas Inventory (GHGI). The model combines the IPCC waste model (IPCC, 2006) with the IPCC first order decay equations describing the carbon storage and emissions of wood products (IPCC, 2019). These equations are supplemented with a self-developed recycling and waste routing module.

The model can be parameterised according to the examined products and conditions. The half-life of the products, the recycling rate, the amount of products incinerated and landfilled can be set, as well as the extent of methane recovery from the landfill gas. In addition, the recycling route can be selected, i.e. it can be specified what type of new product is produced from the wood that has become waste (e.g. particle board from sawnwood).

This demonstration provides insight into the operation of the model by following the life cycle of 200,000 m^3 particle board. This product quantity was chosen because it is comparable to the annual production of a larger domestic wood processing company. During the modeling, 2020 was the starting year when the production took place. Emissions from the products were examined under three scenarios until 2130, i.e., for one hundred and ten years. We investigated such a long period of time so that the relatively slow processes taking place at the solid waste disposal sites (SWDS) can be perceived, and the magnitude of emissions from landfills can be realistically assessed.

In the first examined scenario, it was assumed that the half-life of the products is 25 years (the default value given by the IPCC for particle board). In this scenario, 10% of the products ending their lifespan were recycled and 80% of them were disposed of via landfilling. The remaining amount was incinerated (*Table 1*). The amount of waste going to landfill in this scenario was set to 80% in order to examine the waste management pathway that currently characterises the wood waste (furniture and household items) from households collected by waste management service providers. Especially in areas where wood waste burning is less common in households (e.g., big cities), and where waste materials are not used for heating purposes (waste burning is perhaps less common in the western part of the country), wooden furniture and household items that become waste are handed over to the public waste management service provider.

In the second scenario we assumed 15% solid waste disposal, while in the scenario characterised with combined mitigation measures the recycling rate and the product lifetime was increased (*Table 1*).

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Table 1: **Parametrization of the scenarios**

Year	2020	2050	2130
80% landfilled scenario			
Half-life	25	25	25
Landfilled %	80%	80%	80%
Recycled %	10%	10%	10%
Incinerated %	10%	10%	10%
CH4 recovery %	3%	3%	3%
15% landfilled scenario			
Half-life	25	25	25
Landfilled %	15%	15%	15%
Recycled %	10%	10%	10%
Incinerated %	75%	75%	75%
CH4 recovery %	3%	3%	3%
Combined mitigation measures scenario			
Half-life	35	35	35
Landfilled %	15%	10%	5%
Recycled %	20%	50%	80%
Incinerated %	65%	40%	15%
CH4 recovery %	3%	3%	3%

RESULTS AND DISCUSSION

Figure 1 illustrates the development of carbon storage and the cumulative emissions expressed in carbon dioxide equivalent under the scenario characterised by 80% landfilling. In this case, the carbon dioxide emissions from incineration are insignificant compared to the methane emissions from landfilling. The rate of methane recovery was set to 3% in this scenario, i.e. 3% of the methane from the landfill is collected and burned, the remaining amount is released into the atmosphere in the form of methane. From the climate aspect, methane emissions are more harmful than carbon dioxide emissions. Methane contributes 25 times more to the greenhouse effect that warms the atmosphere than carbon dioxide. Thus, the global warming potential of methane is 25 times higher. This explains the order of magnitude of the methane emissions expressed in carbon dioxide equivalents, and, for this reason, by the end of the examined period, a larger volume of emissions expressed in carbon dioxide equivalents is generated from the examined products than they captured from the atmosphere at the beginning of the process. We can therefore say that the disposal of wood waste by landfilling is the worst option, which in the long term not only offsets the positive effects of the carbon storage capacity of wood products, but actually reverses them. Non-linear trends are attributable to the first order decay equations used to model the decay of wood products in use and the decay of woody material in landfills. This modelling approach is a simplified one suggested by the IPCC (2006; 2019) guidance in order to be able to use relatively simple mathematics. As this mathematical approach is used in the Greenhouse Gas Inventory reporting worldwide it can be regarded accurate as far as practicable. The HWP-RIAL model has been validated based on the Hungarian Greenhouse Gas Inventory reporting.

Figure 1: **Carbon storage and cumulative emissions of 200,000 m^3 particle board under the scenario assuming 80% landfill**

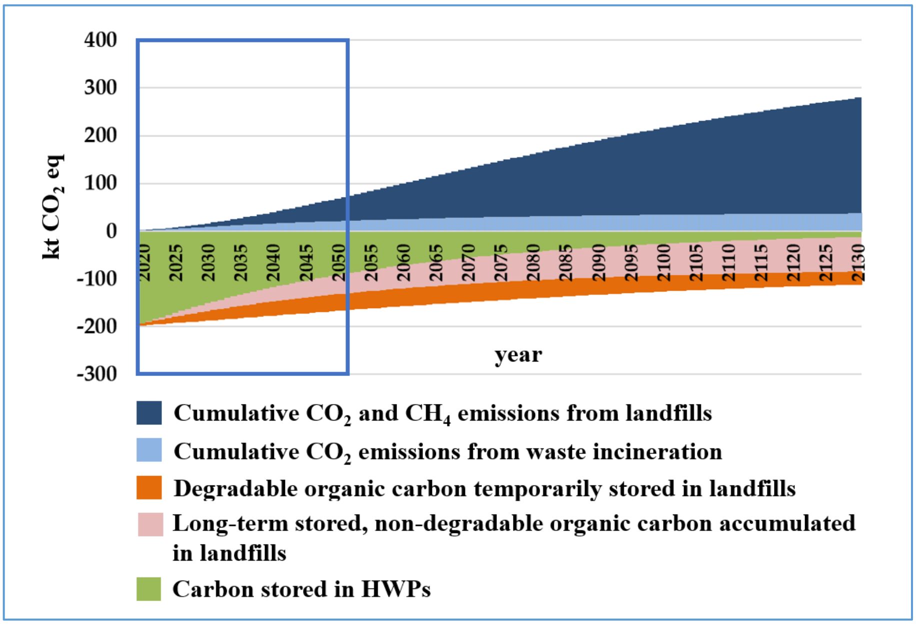

Figure 2 illustrates the carbon storage and emissions associated with the scenario characterised by 15% wood waste disposal. In this case, 15% landfilling was assumed, as this is generally typical in Hungary, according to the data of the GHGI and the National Environmental Protection Information System (OKIR, 2022). In this scenario, 10% of the wood waste was recycled, while the remaining amount was assumed to be incinerated. Under this scenario, methane emissions were much lower, and, consequently, the total emissions expressed in carbon dioxide equivalents were also lower. *Figure 3* shows the carbon storage and

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emissions under the combined mitigation measures scenario characterised by increased product lifetime and recycling rates. In this scenario, the lifetime of the examined 200,000 m^3 of particle board was increased (the half-life was increased from 25 to 35 years), and the recycling rate was gradually increased from 20% to 80%. The level of waste disposal was gradually reduced from 15% to 5% during the examined period. The figure shows that this is the most favorable scenario in terms of carbon storage and emission reduction. Through recycling and the extension of the product's lifespan, the carbon stored in the product remains fixed for a longer time period. The reduction in the amount of landfilled wood waste reduces the level of harmful methane emissions, which are replaced by the less damaging carbon dioxide emissions originating from incineration. These results clearly illustrate the climate mitigation potential inherent in product development and the advantages of the concept of the circular bioeconomy which advocates maintaining the value of products, materials, and resources for as long as possible, whilst minimising waste generation (EC, 2015; Husgafvel et al., 2018).

Figure 2: **Carbon storage and cumulative emissions of 200,000 m^3 particle board under the scenario characterized by 15% of wood waste landfilled**

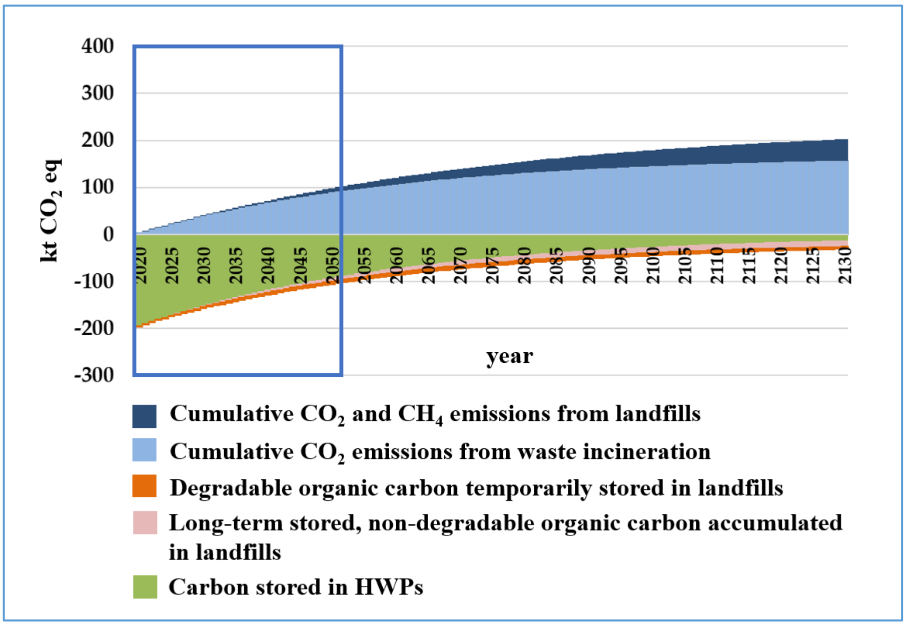

Figure 3: **Carbon storage and cumulative emissions of 200,000 m^3 particle board under the combined mitigation measures scenario characterized by reduced landfilling, increased product lifespan and increased recycling**

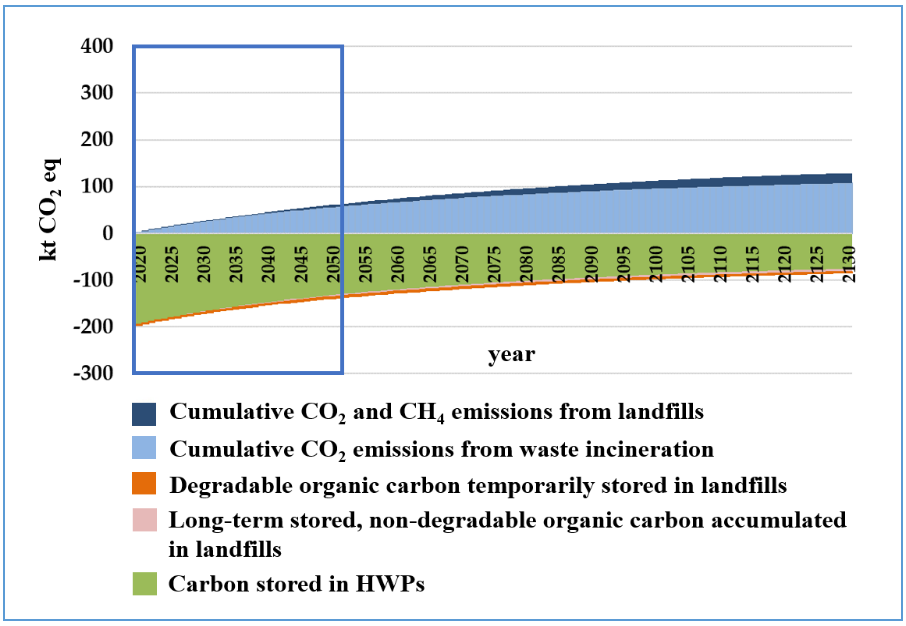

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Figure 4 shows the evolution of carbon storage and emissions until 2050, the date linked to the EU climate neutrality goal. *Figure 5* demonstrates the carbon storage and emissions until the end of the entire examined period (i.e., 2130). The negative consequences of waste disposal have a delayed effect (*Figures 4–5*). When examined until 2050, the scenario characterised by higher disposal could appear even more favorable. At the same time, when examined over a longer period of time, the adverse effect of the methane emissions is already evident, which definitely proves that landfilling of wood waste is the worst option.

Figure 4: **Carbon storage and cumulative emissions of 200,000 m^3 particle board under the three examined scenarios until 2050**

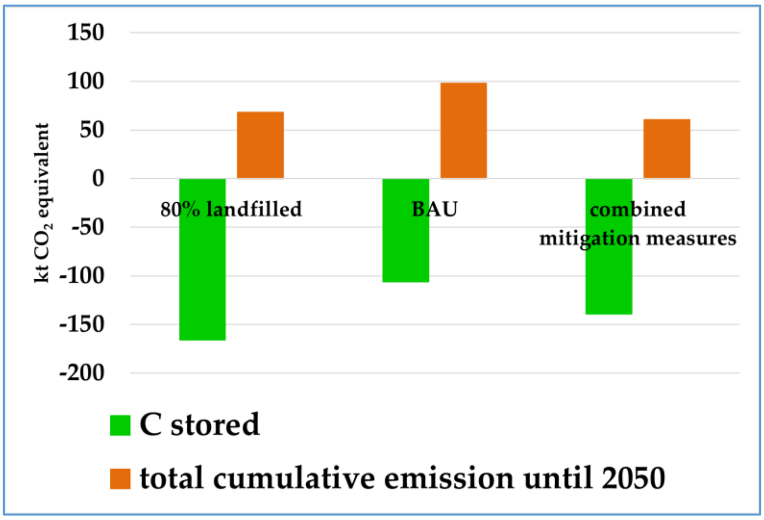
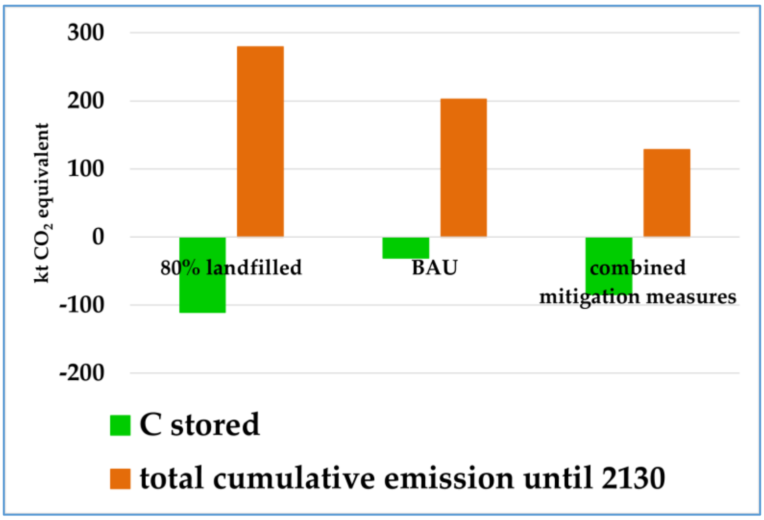


Figure 5: **Carbon storage and cumulative emissions of 200,000 m^3 particle board under the three examined scenarios until 2130**



The third scenario, characterised by combined mitigation measures, has the lowest associated emissions both up to 2050 and over the entire period. This supports the assumption that increasing the lifetime of products, cascade reuse and recycling, as well as reducing the amount of waste going to landfills can significantly contribute to increasing the amount of carbon stored in wood products. Thus, according to the obtained results, the combination of these measures can successfully mitigate climate change.

In the entire examined period (2020–2130), the most unfavorable scenario characterised by high waste disposal resulted in 151 kilotons additional emissions expressed in carbon dioxide equivalent than the scenario characterised by combined mitigation measures. This means that the total emissions that can be avoided by the mitigation measures are equal to 13% of the amount of carbon dioxide sequestered in 2020 by forests planted in the last 20 years in Hungary (NIR, 2022), and to 25% of the annual carbon sequestration realised in wood products at the national level (Király et al., 2022). These numbers illustrate that climate mitigation is not only a policy issue at the national level. Recycling efforts at the company level, and the

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introduction and dissemination of good practices also significantly contribute to the achievement of climate goals.

The limitation of the current version of the HWP-RIAL model is that no country-specific half-life or carbon fraction values are available for particle board. Another limitation of the presented approach is that the emissions associated with the production and transport of wood products have not been considered. Data on production- and logistics-related emissions should also be incorporated in the modelling framework. In the future, we also plan to carry out an uncertainty analysis.

CONCLUSIONS

In this demonstration, we examined the emissions of 200,000 m^3 particle board, a product quantity that is in the order of magnitude of the annual production of the large domestic wood industry companies. Our analysis highlights that even the changes in the use and waste management of such a small product quantity have significant climate mitigation effect. It is our common interest to selectively collect and recycle wood waste, and to prevent this valuable raw material from becoming a source of harmful methane emissions ending up in a landfill.

Our investigations so far show that wood industry has a significant role in achieving the climate goals. Increasing recycling rates and increasing the lifetime of products contribute to extending the carbon storage in wood products. While avoiding the disposal of wood waste in solid waste disposal sites is essential in order to reduce methane emissions.

We conclude that the developed HWP-RIAL model is a suitable tool for the prediction of carbon dioxide and methane emissions related to the end-of-life and waste management of wood products. To facilitate the selection and implementation of the optimal mitigation measures, we will continue our investigations using the HWP-RIAL model as part of the ForestLab project. We will analyse the degree of emission reductions associated with individual mitigation measures. We also plan to use the model to carry out an aggregated national study of the mitigation potential of measures related to the domestic wood industry.

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